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M.S. Chappell

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WIND ENERGY RESEARCH AND DEVELOPMENT

AT THE

NATIONAL RESEARCH COUNCIL CANADA

1975 - 1985

M.S. CHAPPELL

TM-WE-033

NRCC NO. 27459

OCTOBER 1986

This report was compiled by M.S. Chappell from the results achieved by the NRC Wind Energy Research and Development Team and the results of contracted R&D projects carried out by provincial and private agencies in Canada during 1975 to 1985. Members of the NRC team during the decade were:

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This report is dedicated to the memory of Eric Wright who lost his life in the development of wind energy technology.

M.S. Chappell
July 1986

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Summary

Research on wind energy systems began in the Low Speed Aerodynamics Laboratory, National Research Council, in 1966. Initial efforts proved the concepts underlying the technology of vertical axis wind turbines (VAWTs) and confirmed their suitability for electrical generation applications. Following the oil embargo of 1973, wind energy research and development activities were incorporated into the broader NRC program of energy research under the auspices of the Interdepartmental Panel on Energy R&D (PERD). In order to maximize technology transfer to Canadian industry, the majority of the research was done by private sector performers under contract to NRC. National Research Council technical expertize was used to plan and direct the program and to guide and monitor the contractors.

During the decade from 1975 to 1985 the NRC wind energy R&D program continued the development of the VAWT through tests on small models and joint field trials of significant size prototypes in cooperation with potential users such as utilities. Increased understanding of the basic characteristics of the wind resource and the energy conversion systems led to creation of analytical models from which design tools and techniques evolved for use by Canadian industry. Prototype commercial units up to 0.5-MW rating were under test by the autumn of 1984 when the decision was taken for NRC to eliminate its PERD-related energy research activities.

This report chronicles the technical and infrastructural aspects of the NRC Wind energy R&D program during the period from 1975 to 1985. It describes the nature and extend of wind energy resources in Canada. It outlines the basic characteristics and primary relationships of the technology. It provides a current synopsis of the state-of-the-art of wind turbine technology in Canada and enumerates priorities and recommendations for further development. It lists extensive reference material for probing deeper into technical details. It presents a perspective on Canadian achievements and opportunities through summaries of the major wind energy activities in other countries of the Western world.

This document is intended not only as the wrap-up report for NRC's wind energy research and development program, but also as the point of departure for future activities.

WIND RESEARCH AND DEVELOPMENT AT THE NATIONAL RESEARCH COUNCIL OF CANADA 1975 - 1985

M.S. Chappell

1.0 INTRODUCTION

1.1 The Beginnings within the National Research Council

The National Research Council's interest in wind energy began informally in the Low Speed Aerodynamics Laboratory of the National Aeronautical Establishment (NAE). During 1966, aerodynamic research engineers Raj Rangi and Peter South philosophized about a reliable inexpensive means of providing relatively small amounts of energy for pumping water, lighting, and communications to aid developing countries in combating drought, famine, and isolation in rural areas. Not surprisingly, their candidate systems centered on aerodynamic devices that could convert energy from the wind into more convenient forms such as mechanical and/or electrical energy. In an attempt to improve on the somewhat complex traditional windmill, with its machinery atop a tall tower and its need to be oriented into the wind, Rangi and South devised a vertical axis wind turbine (VAWT) configuration with non-adjustable hoop-shaped airfoils that had higher efficiency than conventional high-solidity VAWTs. In addition to being omnidirectional, the new arrangement permitted all the power conversion machinery to be located beneath the rotor and the fixed-geometry rotor was attractive from the viewpoint of easy fabrication and assembly and simple controls. While the first small-scale models were of simple construction (see Figure 1), the concept was proven at larger scale in NRC wind tunnels and on the roof of the Low Speed Aerodynamics Laboratory.

Attempts to patent the new wind turbine in 1967 uncovered the work of Georges Darrieus in France some 40 years previous. Indeed, Rangi and South had "reinvented" the Darrieus VAWT and, moreover, had developed and proved its performance well beyond the work of the original inventor (A-3, A-4).

Research into aerodynamic and structural characteristics of VAWTs continued on a low-key basis within the Low Speed Aerodynamics Laboratory during the late 1960's and early 1970's. The focus initially remained on simple reliable equipment that could provide modest energy supplies to remote areas of developing countries. Analytical techniques were established (A-5) to extend and generalize the experimental performance measurements made in the wind tunnels and outdoors (A-1, A-2). By 1973, studies of potential VAWT applications had broadened to encompass larger electrical units of several

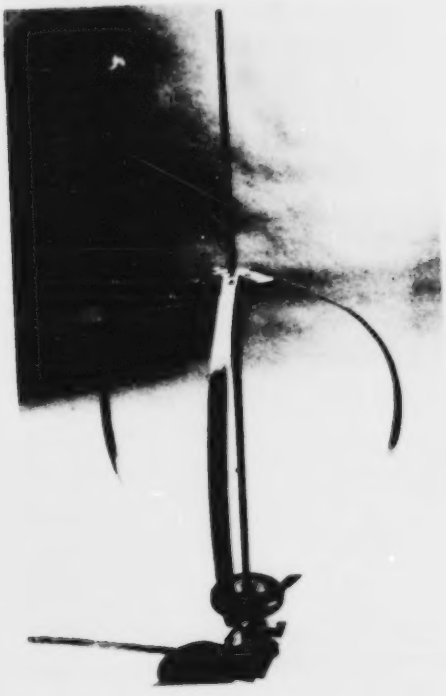

Figure 1. Vertical axis wind turbine, NRC, circa 1966.

hundred kilowatts and arrays of grid-coupled machines contributing to existing energy distribution networks.

The oil embargo of 1973 sensitized oil-dependant nations such as Canada to the strategic vulnerability of oil importation and to the ultimately finite global reserves of petroleum. Canada, like most industrial Western countries, moved swiftly to explore prospects for reducing oil consumption and for incorporating alternative energy sources into national supply networks. Wind energy was among several renewable (or inexhaustible) energy sources whose technical and economic viability were examined as part of a national energy research and development program (F-1).

1.2 Evolution of the Federal Research Program

In the wake of the 1973 Arab Oil embargo, the Cabinet instructed the Department of Energy, Mines and Resources (EMR) to convene a Task Force on Energy Research and Development comprising Deputy Ministers of departments and agencies concerned with energy R&D. The Task Force rejected the concept of forming a central agency for energy R&D in favour of a coordinating agency within EMR and with R&D management and performance in a large number

of existing departments and agencies. Initial requests for new funds followed a review of existing R&D activities and government approval of the report *Energy Strategy for Canada: Policies for Self-Reliance* (F-1).

In July 1975 the Interdepartmental Panel on Energy Research and Development (PERD) was formed to review and assess federal energy R&D, to harmonize those R&D efforts with energy policy, and to prepare recommendations for the appropriate level and distribution of resources. A structure of Tasks and Programs was established to ensure balanced coverage and visibility of the various technical areas, as shown in Table 1.

A specific department or agency within PERD was made responsible for each Task and a Lead Agency was assigned for each Program. The National Research Council was charged with management of the Renewable Energy Task and was the identified Lead Agency for eight R&D Programs, including Wind Energy.

The further shocks to international oil pricing in 1979 led to a second major round of energy R&D initiatives in 1980, as one element within the National Energy Program (F-2). The areas identified for special attention included alternative liquid fuels, efficiency of energy use, new energy sources, and frontier resource technology. The Panel on Energy R&D was charged with overseeing this expansion of the energy R&D program and formed a network of program committees to ensure a breadth of departmental and specialist input into each of the technical programs. These arrangements

Table 1. Federal energy R&D structure 1975-1980

Tasks	Programs
I. Conservation	Buildings Transportation etc.
II. Fossil fuels	Oil Sands & Heavy Oil Coal etc.
III. Nuclear	Fission Fusion etc.
IV. Renewables	(Unconventional) Hydraulic Energy Solar Energy Energy from Biomass Wind Energy Geothermal Energy
V. Transportation of energy	Pipelines Transmission Lines etc.

prevailed up to the decision of the government to reduce the scale and nature of the federal energy R&D program, late in 1984.

Government funds allocated through PERD increased rapidly throughout most of the decade as shown in Figure 2. Distribution among tasks is shown in Figure 3, and the allocations for wind energy R&D are shown in Figure 4.

1.3 Infrastructure Surrounding the Wind Energy R&D Program

In addition to the federal energy research programs, provincial governments and university granting agencies supported scientific and engineering efforts to reduce energy demand and to understand and harness new forms of energy. The National Science and Engineering Research Council (NSERC) recognized energy as one of the major strategic fields for which it provided grants to university researchers. Provincial Ministries of Energy provided resources to develop energy alternatives and industrial opportunities in their regions. Of particular value were federal/provincial joint projects to assess the relative potentials of several alternate energy sources.

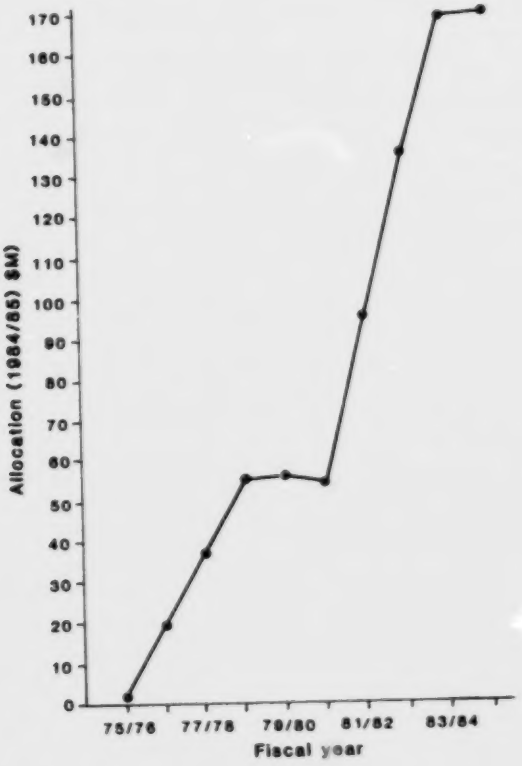

Figure 2. Distribution of PERD funds.

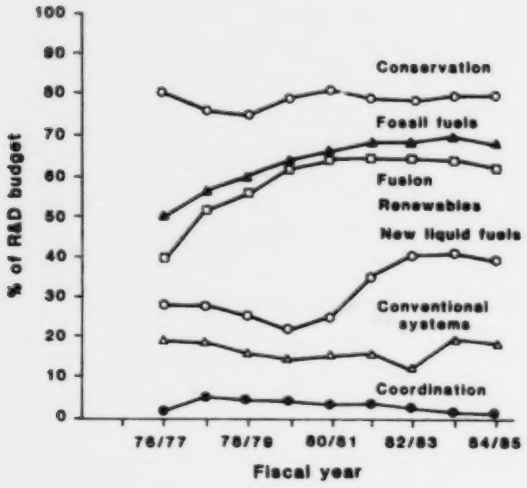

Figure 3. PERD funding for energy R&D.

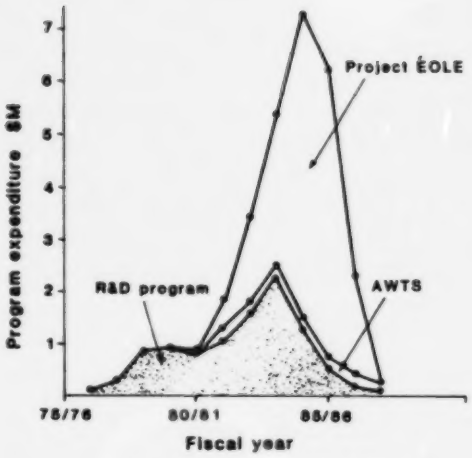

Figure 4. Wind energy R&D funds.

To carry on beyond the R&D initiatives, the federal government created several programs to encourage the demonstration and deployment of the new technologies developed. Among these were

- Canadian Home Insulation Program (CHIP)
- Automotive Fuel Consumption Standards
- Forest Renewable Energy Program (FIRE)
- Purchase and Use of Solar Heating (PUSH)
- Canadian Oil Substitution Program (COSP)
- Energy Demonstration Program (ENERDEMO)

The last of those listed was a particularly appropriate vehicle for initiating wind energy projects in remote communities during the early to mid-1980's.

Industrial incentives, such as the Industrial Energy R&D program (IERD), were also available to assist Canadian manufacturers in production engineering to enhance the commercial viability of new technologies.

To provide economic encouragement for adoption of new, more energy efficient equipment and processes and to enhance the consideration of the generally capital-intensive renewable energy technologies, rapid depreciation was allowed under taxation legislation for certain types of equipment. Though such incentives applied to solar energy systems, they unfortunately were not extended to include wind energy conversion systems, even when such machinery was used to directly offset oil consumption. (This situation was rectified in the February 1986 Budget.)

2.0 THE WIND ENERGY R&D PROGRAM

2.1 Objectives

Though the technical genesis of wind energy R&D in Canada was predicated on concerns for small energy supplies appropriate to rural areas in developing countries, the major effort and resources allocated to the program during 1975-1985 were precipitated by concerns for alternative regional and national energy supplies in Canada. This domestic concern for oil substitutes dovetailed with the evolving technical focus on larger-scale wind energy conversion systems capable of contributing meaningful amounts of energy to community, regional, or national supplies. Accordingly, the broad objectives of the NRC Wind Energy Research and Development program (WERD) were:

- To determine under what circumstances wind energy could make a viable contribution to Canadian energy supplies
- To establish the technology of wind energy conversion systems (WECS) appropriate to Canadian conditions
- To encourage and support Canadian industrial initiatives in the design and manufacture of WECS for both domestic and export markets
- To provide objective technical information on wind energy systems and applications to potential users and manufacturers of WECS

2.2 Scope and Focus

In the mid-1970's many western industrial countries initiated research and development programs to examine new energy source technologies, including wind energy. In Europe and North America previous use of small-scale wind energy conversion systems had been widespread in the 1920's and 1930's, prior to extensive rural electrification. In the new context, however, the challenge was to apply modern scientific and engineering knowledge in the creation of wind energy conversion systems which could make significant and cost-effective contributions to regional and/or national energy supplies. Many nations concentrated efforts on larger and more efficient windmills of the traditional horizontal axis propeller type. Advanced aerodynamic theory, airfoil shapes, and structural dynamic analysis methods developed for airplane propellers and helicopter rotors were applied to the design of HAWTs with rated power outputs in excess of 100 kW. In Canada the repertoire of such techniques was limited, but NAE research on the Darrieus VAWT was relatively advanced.

The existence of extensive electrical distribution networks suggested that "aeroelectricity" was the logical form of integrating meaningful contributions of wind energy into regional and national supplies. Moreover, at somewhat smaller scale, very similar wind energy technology could be applied to diesel-generator systems in remote communities to directly offset oil consumption. Considered relative to these applications the intermediate- and large-scale Darrieus vertical axis wind turbine possessed many attractive features, including:

- comparable performance to HAWTs
- enhanced reliability and cost-effectiveness due to the simple, fixed-geometry configuration
- omnidirectionality - eliminating the need for yaw controls and drives
- drive train at ground level - especially meaningful for large-scale systems where drive train and generator can weigh many tonnes
- troposkien blade shape - minimizing centrifugal bending stress and simplifying structural design
- stall-control aerodynamics - eliminating the need for variable geometry elements to control peak power output in high winds

It was also recognized during the formation of the Canadian WERD program that available resources would be best utilized by concentrating attention on a carefully selected course of investigations, rather than attempting to pursue a broad spectrum of research avenues. The Canadian background in VAWT technology, the ultimate technical and economic potential of this configuration, and the interest of Canadian industry in commercializing this novel technology strongly influenced the NRC decision to concentrate Canadian wind energy research in this area. Nevertheless, a great deal of the systems, controls, and applications research was broadly applicable to all sizes and configurations of WECS.

In the early 1980's several dry summers reawakened interest in windmill-driven pumps for irrigation and cattle watering. In addition to farm-sized units there was potential for considerably larger units for use in district irrigation pumping stations and in pumped-storage hydroelectric powerplants. Following a strong lead established by the Alberta/Canada Energy Resources Research Fund, NRC extended its interest to include standards and evaluation of this form of WECS.

2.3 Structure and Management

The Canadian Wind Energy R&D program comprised three major subprograms:

- Resource Assessment and Site Evaluation
- Research and Technology Development
- Field Trials and Technical Support to Industry

Primary elements in each of these subprograms are listed in Table 2 and the highlights are elaborated in the subsequent chapters of this report.

Program management was assigned to NRC's Division of Energy although the aerodynamic and systems engineering expertise remained centered in the Low Speed Aerodynamics Laboratory of the National Aeronautical Establishment. In addition to line management responsibilities within NRC, the Program Manager reported to the integrated federal energy research structure, technically through the Renewable Energy Task Coordinator, and administratively through the NRC member on PERD. Though seemingly awkward, the WERD group functioned effectively as a team despite the variety of reporting vectors.

Table 2. Canadian Wind Energy R&D Program elements

Resource Assessment and Site Evaluation
Coordination and adaptation of existing data
Analytical and experimental modelling techniques
Calibration and deployment of measuring instruments
Site evaluation and assessment of wind energy potential
Research and Technology Development
Analytical and experimental aerodynamics of airfoils and rotors
Development and verification of structural dynamic design methods
Development of system performance and economic prediction techniques
Investigation of alternative energy extraction techniques
Technical support of major wind energy studies
Field Trials and Technical Support to Industry
Wind tunnel calibration of models of new concepts and of small commercial wind turbines
Support of the Atlantic Wind Test Site, P.E.I.
Six stand-alone systems (special applications)
10 and 100 kW wind/diesel hybrids
Four 50 kW grid-coupled units (remote community applications)
125, 230, and 500 kW grid-coupled units (grid-scale energy supplies)
Design, construction and evaluation of a megawatt-scale turbine (Projet ÉOLE)

Government directives required that, whenever possible, federal research and development activities should be carried out under contract to private sector firms and agencies. This was reflected in the relatively large sum of money made available to the PERD-initiative research programs and the relatively meager increase in staff permitted in those government agencies charged with undertaking the research. Consequently, the majority of WERD projects were performed under contract by private firms and agencies, with NRC staff serving as technical advisors and monitors. This arrangement ensured effective technology transfer to companies potentially interested in commercially exploiting the technology. Interactions with potential users of wind energy technology were achieved through joint field trial projects. Technical goals for the R&D projects were either determined by NRC and subject to competitive tendering by candidate performers or were received (via Supply and Services Canada) and evaluated by NRC in the form of Unsolicited Proposals. A Wind Energy Program Committee, comprising most federal agencies with interest in wind energy technology, advised the NRC Wind Energy Program Manager.

2.4 Level of Effort

Prior to 1973 the federal resources allotted to wind energy research in Canada were minimal. The activities were confined to low-priority projects within the Low Speed Aerodynamics Laboratory at NRC and commanded funding of less than $10K per year and staff of less than 1 P-Y. Between 1973 and 1975, in recognition of the potential of the emerging VAWT technology, NRC engineers South, Rangi, and Templin devoted nearly full time to wind energy. The formation of PERD in 1975/1976 formalized the NRC Wind Energy program as a constituent of the Renewable Energy R&D Task and escalated its resources to $60K. Thereafter funding increased steadily until 1984/1985 when the government decided that resources for energy research should be dramatically reduced and that NRC should no longer participate in PERD energy research programs. Table 3 shows the annual allotments for wind energy R&D throughout the decade. Figure 4 illustrates these data.

Table 3. Federal allocations for wind energy research and development

	75/6	76/7	77/8	78/9	79/0	80/1	81/2	82/3	83/4	84/5	85/6	86/87
$K Program	60	100	282	882	948	681	1162	1549	1591	859	757	-
$K AWTS	-	-	-	-	-	-	184	200	200	200	195	200[1]
$K EOLE	-	-	-	-	-	158	461	1677	3599	6253	4548	904[1]
P-Y NRC	2	2	2	2	2	3	3	3	3	3	2	2
P-Y PERD	0	0	0	0	0	0	4	5	7	7	3	0

[1] Estimated.

Rapid escallation of funding, especially during 77/78 and again in 81/82, without concomitant increases in staff, resulted in the majority of NRC research engineers' time being devoted to technical guidance and monitoring of research being performed by others. Consequently, little in-house research could be done at NRC throughout these years. Such an arrangement is inappropriate in the early phases of a technology, the basics of which are best known to the NRC researchers. The dicotomy of rapidly-increasing financial support and insufficient technical manpower plagued most of the renewable energy R&D programs in the late 1970's and early 1980's. Ironically, the situation was finally being remedied in 1984 when the government substantially eliminated all NRC efforts in these areas.

In addition to the main wind energy research program allotment, funds were designated for two special projects. In April 1981 NRC and Hydro-Québec signed an Agreement to design, build, and evaluate a 4-MW prototype VAWT - Projet ÉOLE. The government's 50% share of project costs are shown as "ÉOLE" in Table 3. Later that same year, NRC signed a 10-year Agreement with the Institute of Man and Resources to operate the Atlantic Wind Test Site (AWTS) on Prince Edward Island as a national WECS testing and experimental research facility. No additional staff were allotted for either of these projects and supervision had to be incorporated into the duties of the NRC team.

2.5 Relation to Other Government Programs

The relation of the NRC wind energy R&D program to potential users and participants in other federal government departments was primarily through the Interdepartmental Panel on Energy R&D (PERD).

As well, NRC's special relationship with the National Science and Engineering Research Council (NSERC) facilitated involvement of the university community in the evolving energy technologies. Indeed, Energy was identified as one of five Strategic Research Areas by NSERC.

Some federal departments with particularly strong energy interests established their own programs that meshed with the PERD Task/Program structure. Four were of special significance to the WERD program.

Throughout the decade very close collaboration was maintained between the NRC WERD program and the Atmospheric Environment Service of Environment Canada (AES/EC). As Canada's national meteorologists and atmospheric aerodynamicists, AES/EC made major contributions to characterization of the wind energy resource (see Chapter 3). As well as transfiguring archived data into forms more convenient for wind energy technologists, AES/EC has performed significant research in analytical techniques for processing wind

data, predicting wind regimes at specific sites, and in instrumentation and procedures for experimental site evaluation.

In the late 1970's Agriculture Canada established the Agricultural Energy R&D program to explore applications of solar and wind energy to agricultural energy demands. After some study (F-3) it was concluded that there were few specific agricultural applications for wind energy technology and that most stationary energy uses on farms could best be addressed by contributions to the electrical grid supplies. In recent years drought conditions in the western Prairies have rekindled interest in windpumps for irrigation and cattle watering. Thus, development work in this area was initiated, primarily under Canada/Alberta joint government sponsorship, and centered around the Lethbridge Windpump Research Station operated by the Alberta Department of Agriculture (Drainage Branch).

Through its Industrial Development Office (IDO) the NRC was able to extend shared cost support to firms wishing to develop energy technologies beyond the stage covered by the research programs. The Program for Industry-Laboratory Projects (PILP) encouraged and supported industrial acquisition and development of concepts initiated within the NRC Laboratories. The work of Bristol Aerospace Limited in developing small autonomous wind power systems for isolated communications stations was supported by PILP. The Industry Research Assistance Program (IRAP) offered a variety of alternative means of enabling (particularly small- and medium-sized) firms to afford research personnel dedicated to specific new products and processes such as renewable energy technologies.

On a much broader scope, the Renewable Energy Division of the Department of Energy, Mines and Resources (RED/EMR) administered programs aimed at encouraging demonstration and deployment of the energy technologies evolving from the research and develoment programs. Through these RED/EMR initiatives, particularly the Remote Communities Demonstration Program (RCDP), the federal government shared the cost and risk of early deployment of fledgling technologies, and simultaneously investigated the economic (cf. technological) feasibility of new systems in realistic situations. This support was of particular significance in helping embryo industrial initiatives bridge the gap between proof-of-concept and commercialization. Preliminary contacts were established with Canada's only federal electric utility agency, Northern Canada Power Commission (NCPC), as a prime candidate partner for wind energy demonstrations in isolated communities with harsh environments.

Ultimately, commercialization of new energy technologies could be supported by the Department of Regional Industrial Expansion through participation in the Industrial Energy Research and Development (IERD) program. However,

this vehicle was directed at support for industrial engineering of products and processes for which technical development was well advanced and for which clear and quantifiable markets were identified.

2.6 International Collaboration

In 1974 the Organization for Economic Cooperation and Development (OECD) formed the International Energy Agency (IEA) as a countermove to the Organization of Petroleum Exporting Countries (OPEC) who had so shocked the world with the 1973 oil embargo. The purpose of the IEA was to provide a vehicle for international collaborative research and development in energy conservation and alternative energy source technologies. Over 20 specific R&D Implementing Agreements were drawn up among countries interested in sharing resources and experience for reducing dependency on imported oil. Most of Canada's international collaborations in energy R&D were channelled through these multilateral IEA Agreements.

The IEA Implementing Agreement on R&D into Wind Energy Conversion System (IEA R&D WECS) was signed in October 1977. In addition to Canada, eight other countries participated initially in four research efforts known as Annexes to the Agreement. As of December 1985 IEA R&D WECS has undertaken nine major cooperative programs of research; their titles, participants, and status are summarized in Table 4. The current Annual Report of the Executive Committee is listed as reference D-16.

In addition to these specific projects, IEA R&D WECS maintains a standing subcommittee on Recommended Practices (D-50 to D-56). To date, five such practices have been published and widely distributed within member nations. Topics include

Vol. 1. Power Performance Testing (D-51)
Vol. 2. Estimation of Cost of Energy from Wind Energy Conversion Systems (D-52)
Vol. 3. Fatigue Characteristics (D-53)
Vol. 4. Acoustics: Measurement of Noise Emmission from WECS (D-54)
Vol. 7. Quality of Power: Single Grid-connected WECS (D-55)

The remaining two volumes, Vol. 5 concerning Electromagnetic Interference and Vol. 6 concerning Safety and Reliability, are in preparation.

In 1977 a second IEA wind energy Implementing Agreement was enacted. In recognition of the increasing potential envisaged for very large wind systems (with rated power outputs of greater than a megawatt), the IEA Implementing Agreement on Large Scale Wind Energy Conversion Systems (IEA LS WECS) was signed with Denmark, Germany, Sweden, and the United States as

Table 4. Research project annexes to IEA R&D WECS

Annex No.	Title	Participants	Started	Finished	Ref.
I	Environmental and meteorological aspects of WECS	AUT, CAN, DNK, FRG, IRE, JPN, NLD, NL, NOR, SWE, USA	1977	1981	D-9 to D-18
II	Evaluation of models for wind energy siting	CAN, FRG, JPN NOR, SWE, UK, USA	1977	1983	D-19
III	Integrating of wind power into national electricity supply systems	FRG, JPN, NLD, SWE, USA	1977	1979	D-20
III(a)			1980	1983	D-21
IV	Investigation of rotor stressing and smoothness of operation of large-scale WECS	DNK, FRG, JPN, NLD, SWE, USA	1977	1980	D-22 to D-33
V	Study of wake effects behind single turbines and wind turbine parks	CAN, DNK, IRE, NLD, JPN, SWE, UK, USA	1980	1984	D-34 to D-41
VI	Study of local wind flow at potential WECS hill sites	CAN, DNK, FRG, NZL, UK	1982	1985	C-1 to C-7 C-24
VII	Study of off-shore WECS	DNK, NLD, SWE, UK, USA	1984	cont.	
VIII	Study of decentralized applications for use of wind energy	CAN, DNK, NLD, SWE, UK, USA	1984	cont.	
IX	Intensified study of wake effects behing single turbines and in wind turbine parks	DNK, NLD, SWE, UK, USA	1985	cont.	

[1] The underlined participant country was the Operating Agent in charge of organizing the particular Annex.

charter participants. At semi-annual Executive Committee meetings detailed design and operating experiences were exchanged to aid all contributers via "lessons learned" in these costly projects (D-15). To enable in-depth technical discussion on specific topics of mutual interest, Specialist Meetings were arranged periodically at appropriate venues within the participating countries. Table 5 lists the dates and topics of the fourteen Specialists' Meetings held to date. Kernforschungsanlage Julich GmbH in Germany has published the Proceedings of each of these meetings for use by wind energy R&D performers in participating countries (D-1 to D-14). Canada joined

Table 5. IEA LS WECS Specialists' Meetings

Meeting No. (Ref.)	Topic	Date and Venue
1 (D-1)	Seminar on structural dynamics	Oct. 1978 Munich
2 (D-2)	Control of LS WECS and adaption of wind electricity to the network	Apr. 1979 Copenhagen
3 (D-3)	Data aquisition and analysis for large scale wind energy conversion systems	Sept. 1979 Blowing Rock, NC
4 (D-4)	Rotor blade technology with special respect to fatigue design problems	Apr. 1980 Stockholm
5 (D-5)	Environmental and safety aspects of the present large scale WECS	Sept. 1980 Munich
6 (D-6)	Reliability and maintenance problems	Apr. 1981 Aalborg
7 (D-7)	Costing for wind turbines	Nov. 1981 Copenhagen
8 (D-8)	Safety assurance and quality control of LS WECS during assembly, erection, and acceptance testing	May 1982 Stockholm
9 (D-9)	Structural design criteria for LS WECS	Oct. 1983 Greenford
10 (D-10)	Utility and operational experiences and issures from major wind installations	Oct. 1983 Palo Alto
11 (D-11)	General environmental aspects of large scale wind energy utilization	May 1984 Munich
12 (D-12)	Aerodynamic calculation methods for WECS	Oct. 1984 Copenhagen
13 (D-13)	Economic aspects of wind turbines	May 1985 Petten
14 (D-14)	Modelling of atmospheric turbulence	Dec. 1985 Stockholm

IEA LS WECS in February of 1982 when government approval for the 4-MW VAWT prototype (Projet ÉOLE) was confirmed. Current membership in IEA LS WECS and the large-scale WECS projects now commissioned or underway are shown in Table 6.

Table 6. IEA LS WECS member nations and large-scale projects

Country	Location (no. units)	Owner/Operator (Manufacturer)	Type/No. blades/ Orientation	Swept area (m^2)	Rated Power (kW)	Rated Wind (m/s)	First Rotation (Scheduled)
Canada	Iles de la Madeleine	NRC/Hydro Quebec (DAF)	V/2/-	595	224	13.5	1977
	Prince Edward Island	NRC/AWTS (DAF 6400)	V/2/-	595	522	19.0	1984
	Cap Chat, Quebec	Hydro Quebec	V/2/-	4000	4000	20.7	(1986)
Denmark	NIBE (A)	DEFU	H/3/U	1257	630	13.0	1979
	NIBE (B)	DEFU	H/3/U	1257	630	13.0	1980
	Koldby	Danish Wind Techy.	H/3/D	661	265		1982
	Langeland	Fynsvaerket	H/3/D	755	300		1985
	Hundested (3 units)	Local Utility Co.	H/3/D	755	300		(1986)
	Masnedo (5 units)	Elkraft	H/3/U	1257	750	15.0	(1986)
	Esbjerg	Elsam	H/3/U	2827	2000	15.0	(1987)
Germany	Schnittlingen	Voith	H/2/D	2124	265	8.5	1981
	Weddenwarden	MBB Monopteros	H/1/D	1810	370	10.0	1981
	Kaiser-Wilhelm Koog	Growian	H/2/D	7854	3000	11.8	1983
	Helgoland	Local Utility Co.	H/3/U	2827	1200	12.0	(1986)
Nether-lands	Petten test site	ECN (HAT-25 Exp.)	H/2/U	491	300		1981
	Flushing	PZEM (NEWECS 25)	H/2/U	552	300	14.0	1984
	Curacao	KODELA (NEWECS 25)	H/2/U	552	300	14.0	1985
	Schiedam	ONS (NEWECS 25)	H/2/U	552	300	14.0	1985
	Medemblik	PEN (NEWECS 45)	H/2/U	1590	1000	13.9	1985
	Sexbierum (18 units)	SEP (Holec)	H/3/U	707	300		(1986)

Table 6 (Continued)

Country	Location (no. units)	Owner/Operator (Manufacturer)	Type/No. Blades/ Orientation	Swept Area (m^2)	Rated Power (kW)	Rated Wind (m/s)	First Rotation (Scheduled)
Sweden	Maglarp	SYDKRAFT (WTS-3)	H/2/D	4778	3000	14.0	1982
	Nassudden	SSPB (Kamewa WTS-75)	H/2/U	4418	2000	12.5	1983
United Kingdom	Carmarthen Bay	CEGB (WTG-200)	H/3/U	491	200	13.4	1982
	Burgar Hill	NOSHEB (WEG MS-1)	H/2/U	314	250	17.0	1983
	Burgar Hill	NOSHEB (HWP-300)	H/3/U	380	300	17.0	1983
	Burgar Hill	NOSHEB (WEG LS-1)	H/2/U	2827	3000	17.0	(1986)
	Carmarthen Bay	CEGB (VAWT-25)	V/2/-				(1986)
	Ilfracombe	SWAEB (WEG MS-2)	H/3/U	491	200/ 250		
	Shetland Islands	NOSHEB (HWP-750)	H/3/U	1590	750		(1986)
United States	Goldendale (3 units)	DOE/BPA (MOD-2)	H/2/U	6504	2500	12.5	1980/1
	Medicine Bow	DOI (MOD-2)	H/2/U	6504	2500	12.5	1981
	Medicine Bow	DOI (WTS-4)	H/2/D	4778	4000	16.1	1982
	Solano	PG&E (MOD-2)	H/2/U	6504	2500	12.5	1983
	Palm Springs	SCE (INDAL 6400)	V/2/-	595	522	19.0	1983
	Palm Springs	SCE (HWP-330)	H/3/U	531	330		1985
	Oahu, Hawaii	HEC (MOD-5B)	H/2/U		3200		(1987)
	Hawaii (15 units)	Westinghouse			600		1985
	Altamont Pass	PG&G (HWP-750)	H/3/U	1590	750		1986
	Altamont Pass	PG&E			200		
	San Gorgonio Pass	SCE (Carter 200)					
	San Gorgonio Pass	SCE					

Technical Workshops and Executive Committee meetings of both IEA Wind Energy R&D Implementing Agreements were scheduled to coincide with major international wind energy conferences. Thus, the interchanges of experience were significantly extended and exhanced beyond the formal IEA projects.

3.0 RESOURCE CHARACTERIZATION AND SITE ASSESSMENT

3.1 Basic Characteristics of Wind as an Energy Source

Wind energy is a manifestation of solar energy. Differential solar insolation and absorptivity on the earth's surface result in non-uniform heating and create high and low pressure areas. Air movement from high to low pressure regions, modified by rotation of the earth and local topographical features, is wind.

A moving airstream contains kinetic power as described by the relation:

[1] $$KP = \tfrac{1}{2}\rho A V^3$$

where

KP = kinetic power (W)
ρ = air density (kg/m^3)
A = area perpendicular to flow (m^2)
V = wind speed (m/s)

The fraction of the kinetic power in the airstream that can be converted to mechanical power by a wind turbine is discussed in Section 4.3.1.

It is noteworthy that the kinetic power is proportional to the cube of wind speed and is also dependent on air density, i.e., pressure and temperature. Kinetic energy in the airstream is determined from the time integral of kinetic power over the period of interest.

[2] $$KE = \int_{t_1}^{t_2} KP \, dt = \tfrac{1}{2}\int_{t_1}^{t_2} \rho \, AV^3 \, dt$$

where

KE = kinetic energy (Wh)
t_1, t_2 = beginning and end of time interval (h)

The flow of wind near the earth is retarded by surface friction and interference with surface features such as trees and hills. Substantially all wind energy conversion systems operate in this boundary layer. The relation between wind speed and height above the local surface has been measured and usually found to conform with the following relation:

[3] $V_2/V_1 = (h_2/h_1)^{\alpha}$

where

V_1 = wind speed at height h_1
V_2 = wind speed at height h_2
α = boundary layer velocity exponent

It is common practice to quote wind speed at a standard reference height of 10 m above the local ground level.

The boundary layer velocity exponent α depends on the type of terrain over which the wind flows. From wind tunnel and field measurements it has been found that the following values of α are usually applicable to terrain with certain degrees of roughness:

Water (at modest wind speed)	$\alpha = 0.10$
Flat open country	$\alpha = 0.16$
Rough wooded country or city suburbs	$\alpha = 0.28$
Heavily built-up urban centers	$\alpha = 0.40$

These relations are plotted in Figure 5.

For preliminary analysis of potential wind turbine sites the value $\alpha = 0.16$ is often used until topographical information and/or site measurements allow a more accurate estimation. For $\alpha = 0.16$ the wind velocity increases 12% with each doubling of height above the ground. From Equation [1] it

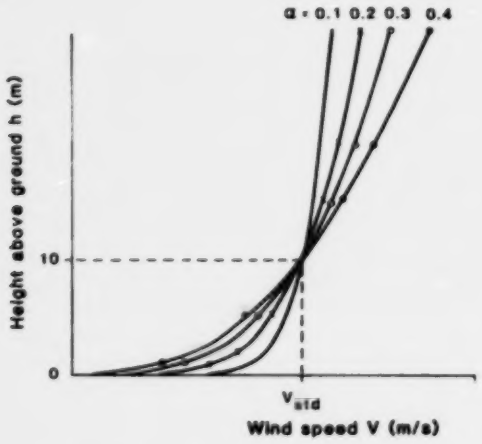

Figure 5. Wind velocity variation with height above ground.

will be noted that a 12% increase in velocity corresponds to about 40% increase in kinetic power in the airstream; thus, wind turbines are usually mounted on tall towers.

Wind velocity varies considerably with time. Figure 6 shows that the periodicity of these variations extends from less than a second (turbulence) to more than a month (seasonal); however, some patterns generally prevail. Wind speeds are usually higher in the winter than summer due to the more frequent occurrence of intense large-scale weather systems. Wind speeds are usually higher on average in the afternoon than in the early morning hours due to daytime heating and the resulting mixing of the lower atmosphere.

At a given location the wind speed exhibits day-to-day variations in levels of turbulence (temporal and spatial variability on the order of seconds and metres respectively in wind speed and direction). Mechanically induced turbulence caused by upstream surface roughness and terrain effects can vary with wind direction and sometimes with season. Thermally induced (convective) turbulence varies with weather pattern, season, time of day, and air-surface temperature difference.

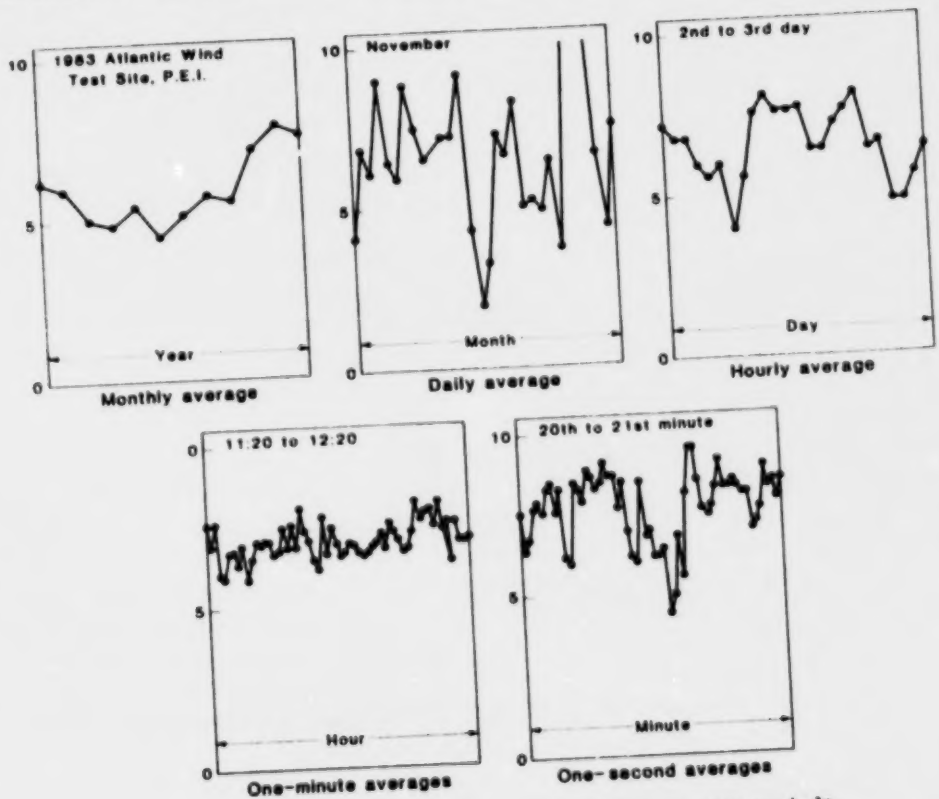

Figure 6. Wind speed averages over different time periods.

The temporal distribution of wind velocity at a given location is commonly described by the Weibull probability function:

$$[4] \qquad (p)(V/V_{ave}) = k(\Gamma + 1/k)^k (V/V_{ave})^{k-1} \exp -[\Gamma(1 + 1/k)(V/V_{ave})]^k$$

where

$(p)(V/V_{ave})$ = probability of a particular wind velocity
Γ = the mathematical gamma function
k = Weibull Coefficient

Figure 7 shows the probability distributions for three values of the Weibull Coefficient k. In each case the area under the curve is unity.

A special case of the probability distribution (called the Rayleigh Distribution) exists when k = 2.0. This distribution is a reasonable approximation to the wind regime at many potential turbine sites. It is often used in preliminary analyses because it permits certain mathematical simplifications. For example, if k = 2.0,

$$[5] \qquad KP_{ave} = \frac{3}{\pi} \rho A V^3_{ave}$$

where

KP_{ave} = average kinetic power in the wind (W)
V_{ave} = average wind velocity during the period of interest (m/s)

Thus, if a given site has an annual average velocity of 8 m/s and a Rayleigh distribution of velocity, the average kinetic power in wind (for

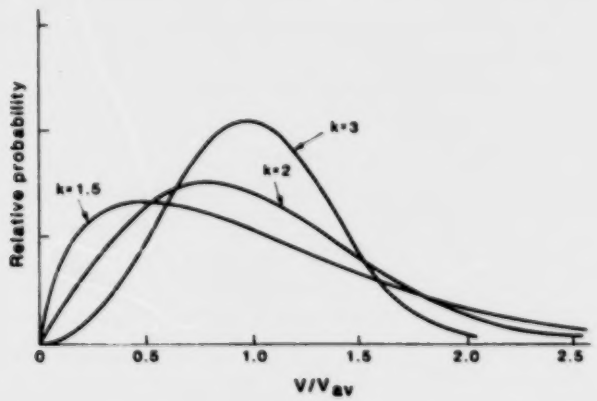

Figure 7. Probability distribution of wind velocity.

standard air density of 1.225 kg/m^3) is 600 W per square metre of area perpendicular to the flow. Hence in one year 5.25 MWh of aerokinetic energy flow though that area.

3.2 Quantifying the Wind Energy Resource at a Specific Site

Although wind speeds can be measured and analyzed for a particular location this can be a costly and time-consuming venture requiring specialized equipment and at least some technical knowledge. There are considerable advantages to being able to estimate at least the mean wind speed at any site with a reasonable degree of confidence from information and techniques that already exist without having to monitor in the field. This would allow for far less costly preliminary screening amongst many potential sites, for example. Of course, on-site monitoring will always give the definitive last word.

Depending on the exact configuration of a proposed WECS installation (grid-coupled, diesel hybrid, etc.), the wind speed information required to make an accurate estimate of the performance of the WECS might include wind speed distribution annually, by month, or by hour of the day, along with other information such as the persistence structure (e.g., how often does the wind speed remain below the cut-in speed of the WECS, for a minimum of 24 h) or turbulence levels. If the site has been monitored then analyses such as those noted above are usually a relatively simple matter if the original time series of wind speeds are retained. The single most important statistic for characterizing the wind resource of the location is the annual mean speed. Estimating the mean wind speed at locations where no measurements are available is an exercise fraught with difficulties.

The Atmospheric Environment Service has in its digital climatological archives the data sets of hourly wind speeds for about 500 locations across Canada. In areas of relatively homogeneous terrain and vegetation, such as the Prairies, the Barrenlands of the Northwest Territories, and to a lesser extent areas of flat farmland in Southern Ontario, the spatial density of anemometer sites (generally from 50 km to hundreds of kilometres) is sufficient to define the major features in the spatial pattern of mean wind speed. One would have some high degree of confidence, for instance, in interpolating from a map on which such a pattern is depicted, for a standard site exposure, of course. However, in many parts of the country, characterized by even moderately rugged or inhomogeneous terrain or variable vegetative cover, the spatial scale of major features in the mean wind-speed pattern is smaller than the distance between anemometer sites. In this case it is only with extreme care and attention to site exposure (both at the anemometer locations and potential WECS sites) that the mean wind speed is estimated.

3.3 Historical Meteorological Data

3.3.1 The Atmospheric Environment Service National Climatological Archives

The Atmospheric Environment Service maintains national climatological archives with records stored on the original reporting forms and other paper documents, microfiche, and in digital form. Records are kept of all observed meteorological elements, including wind speed and direction, temperature, precipitation, solar irradiance, etc. Hourly wind speed and direction data for about 500 Canadian location are available. Earliest data in digital form start in 1952. Supplementary information detailing station history, anemometer height, location, and exposure, although sometimes sketchy especially in the early years, is also available. Two types of wind speed observations have been archived. At most airports one-minute mean wind speed and direction on the hour is observed and archived. At some airports and mainly at climatological stations true one-hour mean wind speeds and prevailing direction are observed and archived. Either is available on nine-track magnetic tape or microcomputer floppy disk format.

3.3.2 Canadian Climate Wind Normals

Summarized wind-speed data for about 500 Canadian locations are available in the AES publication *Canadian Climate Normals, 1951-1980, Volume 5, Wind,* (C-2). The data summarized represent in about equal proportion one-minute mean wind speed and one-hour mean wind speed. Two summary tables are presented for each location which give the mean wind speed by month and direction and the percent frequency of occurrence of each wind direction by month. Other information includes maximum recorded gust speed and station data such as length of record and a brief site description. Although the different averaging periods for the two main types of observation result in some differences in the time series of wind speeds (a series of one-minute mean speeds will exhibit more variability and hence more calm and very high wind speeds than one-hour mean speeds), the long-term mean speeds reported in this publication should have no systematic biases.

The most basic wind-speed data are provided for a wide areal coverage in Canada. Locations tend to be at airport sites or near settlements and so only minimal coverage is provided for locations such as outer windward coasts, ridges, and mountain tops and mountain passes for which the wind energy resource is generally greatest.

3.3.3 Wind Energy Data Analyses for Canada

The AES has prepared a series of wind energy data analyses based on hourly one-minute mean wind-speed data from the AES digital archives for the

10-year period 1967-1976 for 144 selected Canadian locations. The analyses involve the calculation, for each hour, of the wind power from the wind speed at 10 m and air density. The reduced data presentations for each location include four graphs and 13 tables presenting information such as the distribution of wind power with direction, by month, and by hour of the day; wind speed and wind energy frequency distribution; and frequency of duration of periods when the wind speed was less than or exceeded threshold speeds. A description of the calculation procedures has been published by Morris and Howell (C-12). Also included are national maps depicting the mean wind speed and mean wind energy density for the months of January, April, July, and October, and annually (see Figure 8).

The analyses were published in 1986 (C-23) in six volumes, each presenting detailed information for one of the following regions of Canada.

1. Atlantic Provinces
2. Quebec
3. Ontario
4. Prairie Provinces
5. British Columbia
6. Yukon and Northwest Territories

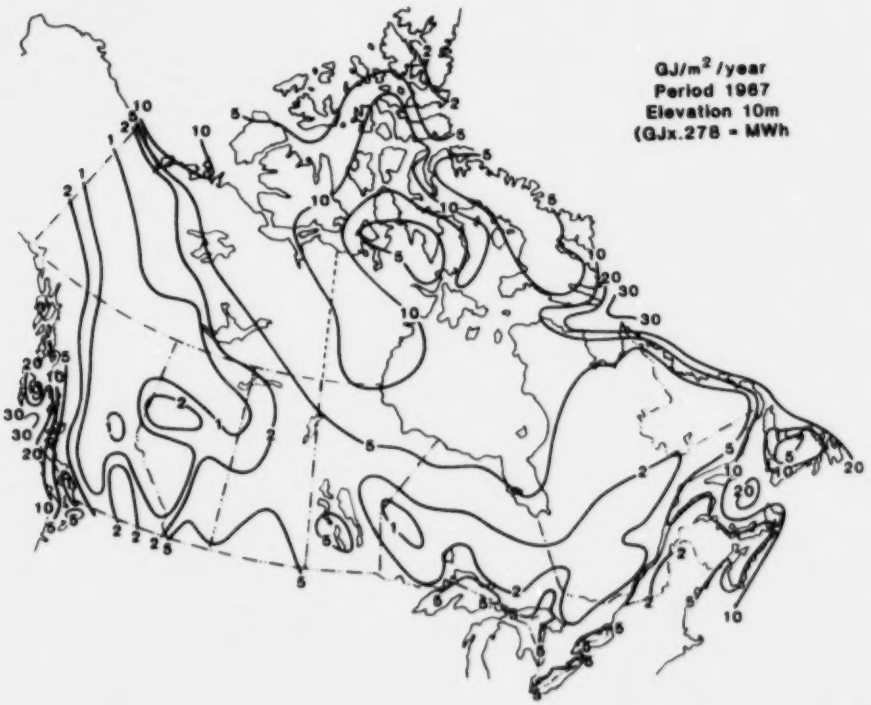

Figure 8. Mean annual wind energy density map.

This represents an updating and expansion of an earlier AES publication (Wind for Power CDS #3-76, 1976), in which the frequency distribution of wind speed at 5-mph intervals and the estimated energy available from each wind-speed class was presented for the month of January (greatest electrical load), the windiest month, and annually for the period of records for 137 Canadian locations.

Parameters of the Weibull distribution, estimated by fitting his commonly used analytical distribution to the annual mean wind-speed distributions at the same 144 Canadian locations as described above, are provided by Morris (C-11). A description of using the Weibull distribution with the power curves of WECS to predict energy yield is included.

3.4 Wind Profiling Projects

The anemometer heights at which AES wind speeds are measured are mostly 10 m. WECS hub or equator heights are generally higher than 10 m, generating the need for estimating the wind resource at heights other than 10 m above ground. Wind speed profiling methods can also be employed in the task of estimating the wind speed in the lower 100 m of the atmosphere from the wind speed at the top of the planetary boundary layer (often from 500-1500 m) when surface wind speeds are not available. Projects directed towards these aspects of wind resource assessment are described in the following sections.

3.4.1 Standardizing the Archived Wind Speeds to 10 m

Although most AES anemometers are located at the World Meteorological Organization's (WMO) recommended height above ground of 10 m, some have been at nonstandard heights. The Meteorological and Environmental Planning (MEP) Company was contracted to investigate and evaluate wind-speed profiling methods and to implement the most suitable one to standardize hourly data sets of wind speeds in the AES archives whose anemometer heights were nonstandard to the standard 10-m height.

Candidate methods were identified from a literature search and a two-year data set of quality controlled tower wind data to 60 m above ground was located for Pinawa, Manitoba, to evaluate the profiling methods. Power law and log law formulations formed the basis of the profiling models tested. Given the observed wind speed at 6.1 m each model was used to predict the wind speeds at the other levels at which the wind speed was measured (25 and 61 m) for every hour in a two-year data set. Evaluation statistics used were bias and root-mean-square errors. None of the models performed remarkably well based on root-mean-square errors, testament to the complexity of the real atmosphere, but average performance was reasonable. The

model judged best was the Irwin model, a power law formulation in which the power law index is allowed to vary each hour with surface roughness and atmospheric stability.

Ten-year hourly meteorological data sets were then prepared for the period 1967 to 1976 for 144 Canadian locations from the AES digital archives. For the 20 locations at which the anemometer heights were nonstandard, the Irwin model was used to correct the hourly wind speeds to 10 m. These data sets were used as input data for the Alberta Research Council's wind energy analysis programs to produce the statistical summary graphs and tables in the Wind Energy Data Analyses for Canada (C-23). Details of the MEP wind profiling analyses project are available in reference C-10.

3.4.2 Wind Profiling to 250 m

Further work was undertaken to evaluate wind profiling techniques in the lowest 250 m of the atmosphere. W.C. Bell of the Department of Geography, University of Winnipeg, Winnipeg, Manitoba, conducted this project. Models evaluated included those tested by the MEP project (see preceding section) with the addition of one or two from the literature. Observations were taken at seven levels from 10 to 243 m at the CBC tower at Starbuck, Manitoba. The results indicated that the Irwin and one-seventh power law models performed best with bias errors generally less than 10% for levels up to 60 m and for unstable and neutral atmospheric stability categories. Models generally performed poorly for higher levels and for stable conditions. Details of this work are published in reference C-3.

3.4.3 Profiling from the Geostrophic Wind Level

This project was undertaken to evaluate the methods to estimate climatological wind speeds in the lowest 100 m of the atmosphere based on climatological records of wind speed at the level of the geostrophic wind (level at which the air flow does not feel the effects of surface friction), used with methods of profiling down to 10-m. Advantages of such an approach include being able to estimate the wind speed at sites where surface measurements do not exist. Concord Scientific Corporation conducted this project. The input data set of geostrophic level wind speed was extracted from a hemispheric six-hourly data set of upper air data based on a 371-km grid covering North America. Methods were chosen to profile from the geostrophic wind level down to 10 m. The same Starbuck, Manitoba, tower data and evaluation statistics as used by Bell (see preceding section) were used to validate the methods.

The evaluation statistics indicated a similar level of merit as the methods used by Bell. An important result was, however, that the methods in this

project performed worst at the lower levels (farthest from the reference wind level, in this case), opposite to Bell's results. Since the grid length (371 km) of geostrophic wind data provides generally less data density than surface anemometer data, and since the surface-based profiling methods performed best in the lower layers, the surface-based methods have been chosen for operational implementation. Details on this project are available from the contractor's reports (C-8, C-9).

In an earlier attempt to identify areas in Canada with high wind energy potential, Templin developed a technique whereby the wind-speed/height exponent α was computed from historical site-specific wind data and the "geostrophic" wind at the upper extent of the atmospheric boundary layer (approximately 500-m height). The geostropic wind is unaffected by topographical features and hence is more accurately predictable. By plotting and smoothing iso-α contours, Templin was able to generate estimated wind velocity data for significant areas, especially in northern Canada, where ground-station data were sparse or non-existent.

3.4.4 Current Procedures

The Atmospheric Environment Service has implemented a wind profiling software package on its mainframe computer which accesses the digital archives. The software allows for the profiling of hourly wind speeds from the anemometer height to specified levels in the lowest 100 m. User input required is the location and its direction-dependent roughness lengths, period of data to be analysed, profiling heights, model to be used in profiling (Irwin or one-seventh power law), and output options (summary statistics including the estimated Weibull parameters are automatically output, the data set of hourly profiled wind speeds on nine-track magnetic tape is optional). The Atmospheric Environment Service will provide service use of this program through their Energy and Industrial Applications Section.

3.5 Site Assessment Projects

Expanding interest in wind energy by potential users and increased field trials of prototype WECS provided opportunities to undertake site specific wind resource assessments at appropriate locations for eventual wind turbine installations.

3.5.1 Anemometer Comparison Project

This project was undertaken to evaluate several commercial anemometers in the rigorous climatic regime on Canada's east coast. About 20 anemometers were purchased by AES and calibrated in the AES wind tunnel for the wind-speed range 0-18 m/s. The anemometers were deployed at the Atlantic Wind

Test Site for an 18-month period where the performance of the anemometers was monitored. A final calibration was performed after the field test. Performance criteria included consideration of catastrophic failure and change of unit calibration. The final report on this project was issued from Resource Ventures Inc., the contractor, in the spring of 1986 (B-33) and is also available from AES.

3.5.2 *National Research Council Wind Prospecting Projects*

In the late 1970's NRC purchased a number of Wind Histogram Recording Systems (WHRS) to automatically log wind-speed data at field trial and potential turbine installation sites. Each system comprised a Climate anemometer mounted on a 20-m tower, a histogram recorder that logged wind speed in 0.5-m/s ranges at 2-s intervals, and a photovoltaic power supply and batteries. The number of 2-s entries in each 0.5-m/s bin was read manually at approximately monthly intervals. The total number of 2-s counts between readings provided a check on data reliability.

In addition to NRC WECS field trial sites, these WHR systems were loaned to potential WECS users to assess particular sites of interest. Utilities, mining companies, provincial governments, and remote communities were among NRC's partners in these wind prospecting projects. In each case the potential WECS user undertook to install the equipment and to acquire and send monthly data sets to Ottawa.

TES Limited, an Ottawa firm of engineers, was contracted by NRC to maintain the field instrumentation, process the data, and publish monthly and annual reports that were sent to all participants. A minimum of one year's continuous data was considered necessary to properly assess a site. Comparisons were made to nearby AES meteorological station data wherever such existed.

In all, about 30 sites were monitored between 1980 and 1985; the annual reports are listed as references E-1 to E-7 inclusive. With the elimination of the NRC Wind Energy Program in 1985, these projects were curtailed, but a small subset continues under EMR auspices. A final report summarizing the site assessments was prepared by TES and is listed as reference E-8.

3.5.3 *Site Selection for Project ÉOLE*

Projet ÉOLE is a joint NRC/Hydro-Québec venture to design, build, and evaluate a 4-MW VAWT (see Section 7.9). The National Research Council arranged for AES to undertake analytical and experimental studies of several potential sites for the prototype unit, as proposed by Hydro-Québec. These activities comprised

- meteorological screening of preliminary sites for the purpose of deciding which sites had suitable wind resource levels to proceed with extensive environmental monitoring;

- management of the data acquisition and analysis from the three 60-m towers at la Fonderie, Pointe Nord-ouest, and Pointe-au-Tonnerre, and from the existing Hydro-Québec towers at Iles de la Madeleine;

- preparation of a digital data base of one-minute and hourly mean wind speed, direction, and temperature from the appropriate heights from each site.

Preliminary activities are described by Taylor and others (C-4, C-15). Preliminary data analyses are described by Salmon (C-13) and by Concord Scientific Corporation reports (C-5, C-6, C-7).

The digital data from approximately two years for the four ÉOLE candidate sites are available from AES on nine-track magnetic tape. The data are available both as original instantaneous values for each minute and as one hour averages for each hour for wind speed at four levels (10, 20, 40, and 60 m, except 18, 27, 36, and 49 m at Iles de la Madeleine) and temperature and wind direction at two levels (10, 60 m except 27 m at Iles de la Madeleine).

Statistical summaries of the data are also available from AES. The mean monthly wind speeds are presented in Table 7 along with the original AES estimates of long-term mean wind speed at each site. The mean wind speed at the AES anemometer site at Mont Joli Airport over the same elapsed two-year period as the monitoring program was run at la Fonderie was 5.3 m/s, 6% less than the long-term wind-speed average upon which the original AES estimate of long-term wind speed at 60-m at la Fonderie was based. A revised estimate using the simple ratio of concurrently observed wind speeds at the same two sites is 8.0 m/s.

The site at La Fonderie, near Cap Chat on the Gaspe Peninsula, was selected for the prototype ÉOLE. Further meteorological data will be obtained once the VAWT is commissioned in the autumn of 1986.

3.5.4 Wind Regime Assessment for DELTX Windpump Tests

In support of the ACERRF project to evaluate the DELTX high-capacity wind turbine water pumper, AES managed the wind data acquisition aspects of the project. AES anemometers and data loggers were installed on site in Calgary. Raw wind and temperature data on cassettes were sent to AES for quality control and analysis. The processed data were returned to DELTX.

Table 7. Mean Monthly Wind Speeds (m/s) at Candidate ÉOLE Sites

Month	La Fonderie 60 m Sep 81 to Aug 83	Pointe au Tonnerre 60 m Sep 81 to June 83	Pointe Nord-Ouest 60 m Sep 81 to Jun 83	Iles de la Madeleine 49 m Jul 82 to Apr 84
January	9.6	8.2	9.1	8.9
February	8.3	6.6	9.4	9.6
March	7.1	7.4	8.5	8.1
April	9.1	8.0	7.4	8.5
May	5.5	7.1	6.6	5.3
June	6.3	7.2	5.4	6.5
July	6.6	6.2	6.1	7.5
August	7.4	6.4	4.7	7.6
September	7.3	6.3	5.9	7.8
October	7.3	7.0	7.6	9.0
November	9.2	7.3	7.2	10.6
December	8.2	7.6	8.3	11.0
Annual	7.6	7.1	7.1	8.4
Original AES estimate of long term mean wind speed	9.0	6.7	8.1	9.4 (60 m)

The data acquisition period was intermittent, spanning the period from May 1984 to April 1986.

3.5.5 *Wind Turbine Wakes*

In a cluster of wind turbines, downstream units can be adversely affected by the wakes from upstream units. In addition to the velocity decrement caused by energy extraction, increased turbulence in the wake of one unit can jeopardize fatigue life of machines immersed in the wake. Templin analyzed the performance loss for downstream members of wide-spread arrays of wind turbines as a function of the number of rotor diameters between units (A-7).

Also, AES adapted a linearized, two-dimensional model of wake decay in the surface atmospheric boundary layer for use in estimating wind-speed variations in the lee of a row of wind turbines. The results could be used to estimate the wake effect power reduction in wind farm arrays and to assist with optimal design of arrays for a given distribution of wind speed and direction. The work is reported in papers by Taylor (C-25, C-26).

3.6 International Collaborations

International collaboration in wind resource characterization and site assessment has been carried out through Canada's membership in the IEA Implementing Agreement for Research and Development of Wind Energy Conversion Systems (IEA R&D WECS). The technical work was performed by AES under Financial Arrangements from the NRC Wind Energy Program.

3.6.1 Evaluation of Models for Wind Energy Siting (Annex II)

Work was undertaken to evaluate the performance of numerical mesoscale meteorological models in estimating the wind flow over specified terrain of domain size typically 10 to 100 km. The AES Small Area Model (SAM) was evaluated along with one United Kingdom and two American models. The merit of each in correctly estimating wind flow over regions in Hawaii, Nevada, and the island of Gotland, Sweden, was evaluated.

The AES SAM uses as input values large-scale meteorological variables (such as surface geostrophic wind speed and direction, 850-mb temperature) and digitized values of surface terrain height, roughness, and temperature over the grid domain. The model output specifies values of surface (10 m) wind speed and direction at each grid point.

The SAM performed well for the Gotland runs and rather less successfully for the Hawaii and Nevada runs. This is attributed to the relatively rugged terrain in the latter two cases. The SAM is not recommended for terrain slopes exceeding 1:40.

The full test results are available in the IEA Annex II report (D-27). Details of the SAM and its performance were reported by Venkatesh and Jessup (C-22), an attachment to the above noted IEA report, and in reference C-24.

3.6.2 Study of Local Wind Flow over Potential Hill Site (Annex VI)

The purpose of the Annex VI work was to obtain a detailed, reliable set of full-scale data describing the mean wind and turbulence structure in the atmospheric boundary layer over a low, isolated three-dimensional hill, and to compare these measurements with the predictions of mathematical and wind tunnel simulations of the same flow. This was done in part to provide a data-base for the assessment of mathematical and wind tunnel models as analytical tools to aid characterization of the wind energy resource on similar terrain features. Canada (AES) was the Operating Agent for this task. Five participants (Canada, the United Kingdom, Denmark, New Zealand, West Germany) were involved in the full-scale measurement program carried out in

two phases in the autumns of 1982 and 1983 at Askervein in the Scottish Outer Hebrides.

A full description is available in the IEA Annex VI reports by Taylor and Teunissen (C-16, C-17). Other accounts of the work include references C-18, C-20, and C-21.

Related work included simple guidelines or rules of thumb to estimate relative wind speed-up factors on hill and ridge tops, described by Taylor and Lee (C-14). An operational computer model, the Ms3DJH/3 model, described by Taylor et al. in reference C-19, is available to more rigorously estimate the wind flow over terrain features.

Comparison of guideline and model results with measurements shows good agreement and indicates their potential value as analytical tools to characterize the wind energy resource for the appropriate terrain scale and configuration. Some details are given in Walmsley and Salmon (C-24).

3.6.3 *Study of Decentralized Applications for use of Wind Energy (Annex VIII)*

The first part of this two-phase collaborative effort concerns techniques for siting wind/diesel powerplants for remote communities not connected to major grid networks. Though initially aimed at serving near-term wind energy markets in IEA member nations, the siting and conversion system technology should be directly applicable to Third World situations. Continued AES and NRC involvement in this project will depend on EMR support.

4.0 WIND ENERGY CONVERSION SYSTEMS

A Wind Energy Conversion System (WECS) is any device which converts kinetic energy from a moving stream of atmospheric air into a more convenient form of energy for the application under consideration. The most common form of WECS output energy is electricity; however, many WECS are used to pump water, to heat space or fluids, and to grind grain, saw wood, and similar mechanical applications.

The term windmill is usually confined to equipment for grinding or milling applications. The term windpump is often used to describe machines in which the pump is driven mechanically by the rotor. Terms such as wind turbine, wind powerplant, aerogenerator, and the more general term WECS are usually used to describe electrical generation systems.

Most windmills of old and all modern WECS are designed to operate automatically. Human intervention is only scheduled for occasional maintenance. Thus, the systems must self-regulate and protect themselves and the loads they are supplying, not only during normal operation but also during occasional partial system malfunctions and under extreme weather conditions.

4.1 Basic Configurations

Most wind energy conversion systems comprise five major components (Figure 9):

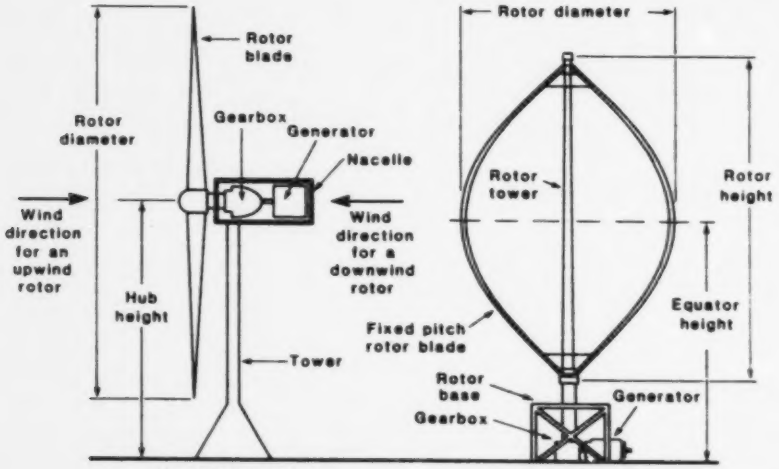

Figure 9. Wind energy conversion system components.

Rotor	consisting of a number of aerodynamic surfaces which, when exposed to the wind, extract aerokinetic energy from the wind and convert it to mechanical energy on a rotating shaft or reciprocating mechanism
Drivetrain	which comprises shafts, bearings, gear boxes, brakes, and other mechanisms which match the characteristics of the rotor power output to the input requirements of the final energy transformation device such as the generator and pump
End-form device energy	comprising the generator, water pump, hydraulic pump, or grindstone that provides power to the application in the form desired
Support system	which comprises the foundations, tower, guycables, and other equipment used to support the rotor and perhaps other components
Control system	by which the operation of the entire system is governed in accordance with wind conditions and load requirements, and which protects both the WECS and the load in the event of unacceptable circumstances

There are two common configurations of WECS, named for the direction of the axis of rotation of the rotor. Horizontal Axis Wind Turbines (HAWTs) have their axes of rotation parallel to the ground, and hence parallel to the wind (Figure 9a). The drivetrain and end-form energy device are usually mounted behind the propeller-type rotor and the entire sub-assembly must swivel on the top of the tower to keep the rotor pointing into the wind.

Vertical Axis Wind Turbines (VAWTs) have their axes perpenticular to the ground and hence can accept wind from any direction (Figure 9b). The drivetrain and end-form energy device are usually housed in a power module at the base of the rotor. The upper bearing of the rotor can be supported by guywires or an external structure, or in some cases the rotor can be cantilevered from the power module.

Most WECS designed for electricity generation have relatively few slender blades as these features tend to give high aerodynamic efficiencies at relatively high ratios of blade speed over wind speed (thus the gear ratio to match rotor speed to standard generator shaft speed is lower and the gearbox is cheaper and more efficient).

For lower speed applications such as pumping or grinding (especially those that require high torque to start the end-form energy device) multiblade or

high-solidity rotors are preferable. Solidity refers to the projected area of the blades divided by the area swept by the blades as they rotate. Traditional American farm windmills have relatively high-solidity rotors; modern aerogenerators with two-or-three-bladed rotors have low solidity.

Low solidity HAWTs and VAWTs have about equal peak efficiency, although each basic type has particular advantages and disadvantages as will be outlined in later sections.

4.2 Typical System Applications

4.2.1 Grid-coupled Alternating Current Systems

Perhaps the simplest application of an electrical generation WECS is to connect it directly into an electrical distribution network. If the relative size of the WECS is small compared to the other generation devices supplying the network there is no concern about overall system stability and the WECS control system can lock onto the frequency and voltage of the grid. This permits use of simple and inexpensive induction motor/generators as well as synchronous alternators and results in nearly-constant WECS rpm when generating.

Certain wind/diesel systems can be considered grid-coupled if the total WECS rating does not exceed 10% to 20% of diesel-generator rating. This will ensure that there is always sufficient diesel generation on line to maintain control of the network.

Much larger grid-coupled systems are prevalent in California where thousands of submegawatt WECS are coupled to the main Southern California Edison (SCE) and Pacific Gas and Electric (PGE) networks. Despite the aggregate WECS rating of over 1000 MW they represent only about 5% of the grid capacity and hence have little or no effect on frequency or voltage stability even in periods of minimum demand and high wind.

4.2.2 Autonomous Alternating and Direct Systems

In smaller systems, or where wind energy penetration is a significant fraction of demand, it is necessary to design the WECS control system to maintain frequency and voltage within limits autonomously. For most ac systems this means precise governing of WECS rotor speed even in gusty wind conditions; thus, the controls must be sufficiently responsive and powerful to regulate the high inertia rotor/drivetrain system. In some ac WECS the wind turbine rotor is decoupled from the grid by electrical equipment such as a static frequency converter which accepts various ac frequencies proportional to rotor speed, converts the electrical power to dc, and

reconstitutes grid-compatible constant frequency/voltage ac for network interconnection. ÉOLE, Canada's 4-MW VAWT prototype, is fitted with a static frequency converter system. Allowing the rotor to operate at variable speed increases energy conversion efficiency by about 10% but has deleterious ramifications on certain structural dynamic aspects (see Section 4.3.3).

Small aerogenerator systems such as those providing power to telecommunications relay stations and navigational aids are often fitted with DC generators that charge batteries from which the load is fed. In such applications the WECS control system must cater for all combinations of wind speed and battery charge level.

Recent economic studies by Mechron Engineering (A-46) have suggested that battery-fed power systems are cost-effective up to sizes appropriate to small isolated communities. The savings achieved by the WECS are augmented by more efficient "Cycle Charge" operation of the diesel generator. It is hoped that, under EMR auspices, a prototype of such a system can be built and monitored to verify these studies.

Similar studies in the United States, United Kingdom, and Denmark have confirmed the attractiveness of various amounts of energy storage in wind/diesel power plants. The large time-variance of wind power limits its penetration in supplying community loads. Energy storage can provide a temporary sink for momentary excesses of wind energy during gusts, allowing retrieval during subsequent lulls. Very short-term storage can be used to smooth the more rapid fluctuations of WECS output caused by wind turbulence or by the nature of the conversion machinery.

In electrical systems, batteries are the most common form of storage, though they present some drawbacks such as necessitating rectification and inversion equipment and usually some form of environmental protection. Also, in most system studies it has been found that the rate of power transfer into and out of storage governs the battery capacity, rather than the energy storage required. Other storage media, including hydraulics, pneumatics, and flywheels, are currently under active study.

4.2.3 Pumping Systems

Using wind energy to pump water dates back many centuries. Large areas of the Netherlands were reclaimed from the North Sea by thousands of massive Dutch windpumps. In North America over eight million small waterpumping turbines provided irrigation and cattle watering before rural electrification in the late 1920's and early 1930's rendered them obsolete.

Most small windpumps use high-solidity HAWT rotors to drive positive displacement reciprocating pumps through some sort of slider-crank drivetrain mechanism. More recently airlift pumps and electrically or hydraulically coupled systems have been introduced - the former to avoid freeze-up and dry-well problems and the latter to permit better siting and operation of the wind turbine.

It has been proposed that large arrays of windpumps could be used to return water to the upstream side of hydroelectric dams, thereby allowing its re-use through the hydraulic turbines. Such a system is known as a pumped-storage hydroelectric plant because the wind energy is "stored" in the form of pumped water until the load demand warrants its use. In this way, as in the use of irrigation reservoirs, the wind energy is temporarily decoupled from the load, thus permitting full use of the wind energy captured.

4.3 Basic Characteristics

4.3.1 Performance and Energy Production

All wind turbines have a performance curve similar to that shown in Figure 10. Below some cut-in wind speed the rotor will not generate sufficient torque to overcome system inertia and friction. As wind speed increases above cut-in, turbine power output increases rapidly, approximately as the cube of wind speed. At some prescribed wind velocity turbine power output reaches the rated capacity of the drivetrain and/or end-form energy conversion device. Further increase of rotor power output is prohibited to prevent overloading the system. Various means are used to achieve power levelling as outlined in Section 4.3.2. Beyond some maximum cut-out wind speed most WECS are shut down to prevent overstressing. Though power output would be great, such high-speed winds occur so infrequently that no substantial amount of energy is produced; also operation in very high-speed wind can significantly reduce fatigue life - thus cut-out is a "designer's choice" and indeed some WECS do not have a cut-out wind speed. Typical values for electrical generation WECS are

$$V_{\text{cut-in}} \approx 4 \text{ m/s}$$
$$V_{\text{rated}} \approx 10 \text{ m/s}$$
$$V_{\text{cut-out}} \approx 20 \text{ m/s}$$

Various analytical methods have been developed to predict wind turbine performance from aerodymanic principles applied to the specified rotor geometry. The major techniques are outlined in Section 5.1.

Performance of different types and sizes of wind turbines can be compared using nondimensional parameters as shown in Figure 11.

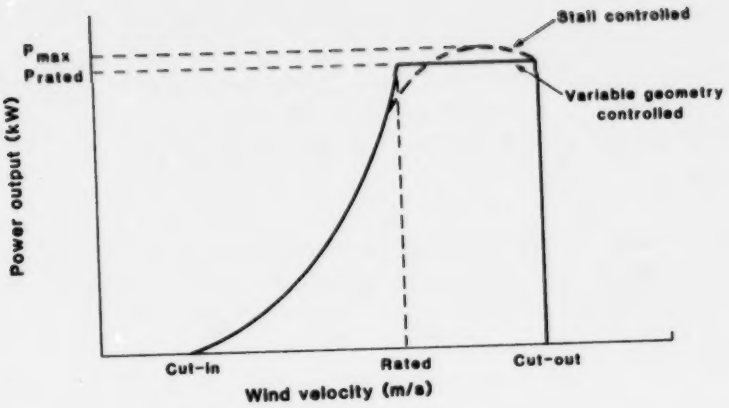

Figure 10. Typical WECS performance curve.

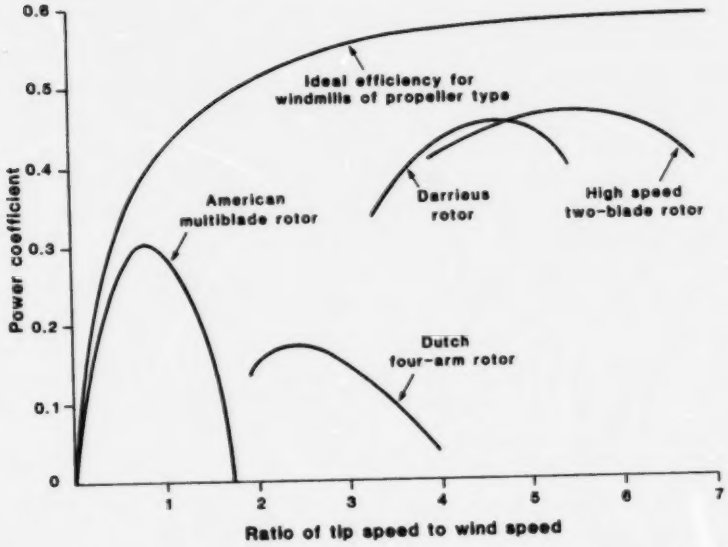

Figure 11. Nondimensional performance of various types of wind turbines.

The ordinate "Power Coefficient - C_p" is a parameter expressing turbine efficiency in converting aerokinetic power in the wind to mechanical power, viz.

$$[6] \qquad C_p \equiv \frac{\text{Power Out from the Rotor}}{\text{Aerokinetic Power Approaching the Rotor}} = \frac{P}{\frac{1}{2}\rho A V^3}$$

Aerodymanic theory decrees that C_p cannot exceed 0.593 - the so-called Betz Limit - for unshrouded rotors. Typical maximum values range between 0.2 and 0.4 for various wind turbines as shown.

The abscissa "Tip Speed Ratio - TSR" is the ratio of the speed of the fastest-moving part of the blade (usually the tip; the equatorial section in curved-blade VAWTs) to the wind speed, viz.

$$[7] \qquad TSR \equiv U/V = R_{max}\omega/V$$

where

U = blade tip speed (m/s)
V = wind velocity (m/s)
R_{max} = largest radius of blade (m)
ω = rotational speed (rad/s)

The value of TSR where the right-hand branch of the C_p-TSR characteristic cuts the abscissa indicates the zero-load or "runaway" TSR, and thus gives an indication of the highest speed the rotor might reach if the load were not connected.

For constant-speed turbines, such as are often used to provide grid-coupled electricity, a broad C_p-TSR characteristic denotes that the rotor will operate near its maximum efficiency over a broad range of wind speed. Conversely, a narrow or peaky C_p-TSR characteristic suggests rapid decreases of rotor efficiency as TSR varies from its optimum value; thus, to maintain high efficiency over a range of wind speeds, variable rotational speed may be desirable. Low solidity rotors whose C_p(max) occurs at a high value of TSR are generally most efficient at high rpm but often do not have very great starting torque. Thus, they are well suited to electrical generation applications. High solidity rotors whose C_p(max) occurs at a low value of TSR generally operate best at low rpm, have high starting torque, and are well suited to pumping applications.

Energy output per year can be computed by integration of the product of the WECS power curve and the wind speed - duration curve that describes the site wind regime. This process is illustrated in Figure 12. From the site wind regime curve it is determined that the wind velocity is V for a total of T hours per year. From the WECS performance curve it is determined that at wind velocity V the WECS produces P kilowatts of power. Thus the energy produced during the whole year at wind velocity V is P × T kWh. Repeating this calculation for all wind velocities between cut-in and cut-out and summing the energy values gives the total annual energy output for that WECS in that wind regime, assuming the machine is available to operate at all times (i.e., no down time). This, and other similar methods have been programmed on personal size microcomputers and reported in the open literature (A-30, A-33).

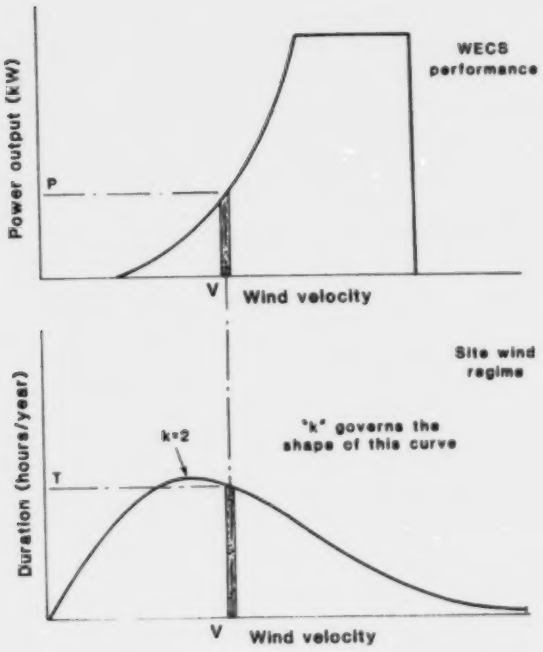

Figure 12. WECS energy output calculation.

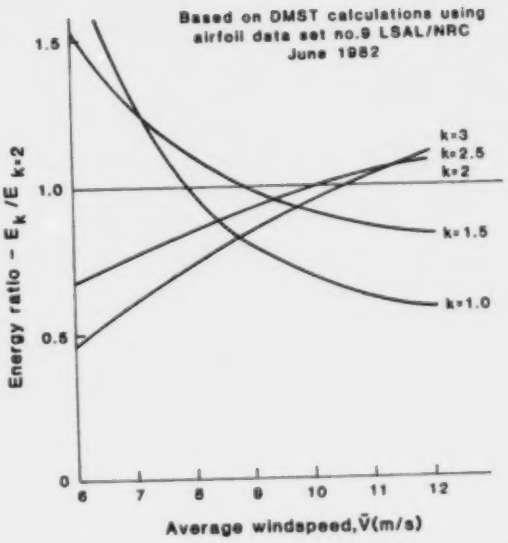

Figure 13. Effect of Weibull coefficient k on WECS energy output.

It is common practice in estimating WECS performance to assume the Rayleigh distribution (k = 2.0) for the velocity-duration curve describing the wind regime. This approximation is justified in many instances; however, non-Rayleigh distributions have been observed at some sites although no quantitative correlation of k value and topographical features has yet been established. The effect of non-Rayleigh wind-speed distribution on energy yield is not negligible and depends also on the average wind velocity. Again using typical current-technology WECS performance, the energy ratio for non-Rayleigh k has been computed and is plotted as a function of annual average wind speed in Figure 13.

The significance of non-Rayleigh values of the Weibull Coefficient k is seen to be greatest at low and moderate average wind speeds. Except in extremely energetic wind regimes, energy yield is greatest at $k < 2.0$. Indeed, the energy output gain is substantial if $k < 1.5$ in moderate wind regimes with $V < 6$ m/s.

4.3.2 System Optimization

It is clear from Figure 12 that some matching of WECS performance and site wind regime is necessary to maximize energy output. Wind energy conversion

systems with high cut-in and cut-out wind speeds are appropriate to windy sites with significant durations of high winds. Conversely, for modest sites with predominate periods of low winds one would prefer a WECS with low cut-in wind speed as long periods of operation even at low power outputs provide considerable energy. In essence, matching WECS performance to site wind regime can be imagined as sliding the power curve to the left or right in order to maximize the energy integral.

A significant parameter in determining the shape of the WECS power curve is the relative size of the rotor and the end-form energy conversion device. For electrical machines this "power loading" parameter is expressed as

[8] $$PL \equiv P_{max}/A$$

where

PL = Power loading (W/m^2)
P_{max} = Maximum or rated power (W)
A = Rotor swept area (m^2)

The power loading is a measure of the designer's choice of how large a generator to attach to a given size of rotor. The energy yield is somewhat sensitive to this parameter, as a very big generator coupled to a given rotor will only be effectively used in very strong winds; thus, in a poor or moderate wind regime such a "mismatched" system will actually produce **less** energy than the same rotor driving an appropriately smaller generator. This is illustrated quantitatively in Figure 14 (derived from reference A-30).

From Figure 14 it is evident that significant penalties can be incurred if power loading is not chosen appropriately for the site wind regime. In poor wind regimes (with annual average wind velocity $V < 5$ m/s) power loadings should be kept below 250 W/m^2. In moderate wind regimes, energy yield is less sensitive to power loading, and units with power loadings between 500 and 750 W/m^2 yield within ±10% of the same energy output over a range of average wind speeds from 5 to 7 m/s. In energetic wind regimes with annual average wind speeds over 7 m/s, power loadings of 750 W/m^2 and above are appropriate.

Alternatively, for the ranges of parameters shown on the graphs, a power loading of 500 W/m^2 results in a 25% loss of energy yield at 4 m/s annual average wind speed, optimum yield at about 5.5 m/s, and a loss of 30% in energy yield at 10 m/s, compared with optimum values of power loading in each case.

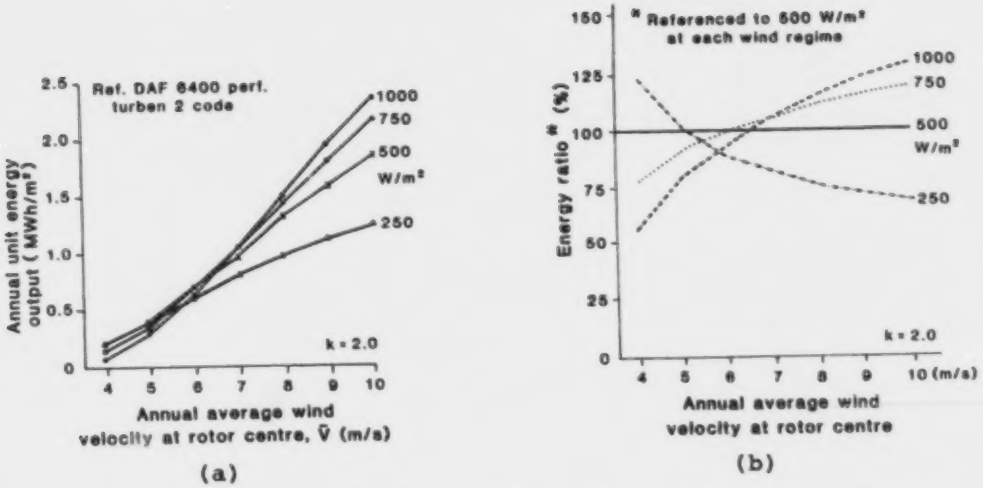

Figure 14. Effects of power loading on energy output as a function of wind velocity. (a) annual energy output per unit swept area, (b) relative energy output.

Rough optima are shown to be:

Annual average wind speed (m/s)	Power loading (W/m^2)
<5	<250
5 - 6	500
6 - 7	750
>7	>1000

In addition to total energy yield, power loading affects the operational behaviour of the WECS. A machine with high power loading will tend to provide high power output for relatively short periods of time (only during very high wind speeds). A machine with somewhat lower power loading may indeed generate the same amount of total energy yield but at lower power output over longer periods of time. The latter is usually preferable and hence, all else being equal, the machine with the lower power loading (within the "roughly optimum" range) is often the wiser choice. Also, generator and drivetrain costs are usually less for machines with lower power loadings.

The term "plant factor" is often used to describe the average fraction of a WECS rated power that is produced. Plant factor is defined by

$$PF \equiv \frac{OE}{T(h)\ P_{max}}$$

where

PF = Plant factor
OE = Output energy (Wh) in time period T(h)
P_{max} = Maximum or rated output of the WECS (W)

Typical plant factors for well-designed WECS at moderately windy sites range between 0.2 and 0.3.

4.3.3 Structural Considerations

Though they are apparently simple structures, most wind turbine components are subject to cylic loads which demand the designer pay close attention to resonant modes and frequencies and to materials and fatigue life of both the stationary and the moving structures. In low-solidity HAWTs the cyclic loading arises from the reversing gravitational forces on the blades as they rotate and from the different aerodynamic forces caused by wind shear and turbulence. In the VAWT configuration the gravitational and centrifugal forces are steady but the aerodynamic forces are cyclic as the rotor blades pass from crosswind, to downwind, to crosswind, to upwind during each revolution.

In addition to steady and cyclic loads transmitted by the rotor, a wind turbine support structure is subject to loads caused by aerodynamic drag, seismic disturbances, and the erection process. The structural dynamic behaviour of even the nonrotating components such as guy wires and towers must be analyzed to ensure avoidance of resonant excitations. Indeed, the structural dynamic characteristics of the rotating and stationary components are usually closely inter-related, as for example between the rotor and guywires of a Darrieus VAWT.

Analytical procedures for predicting resonant modes and frequencies of wind turbine rotors and support structures are generally very complex and often make use of packaged structural dynamic analysis programs such as NASTRAN, GAROS, and others.

The designer's objective is to prevent significant structural resonances from coinciding with excitation frequencies caused by the cyclic loadings. The resonant frequencies of many rotor modes are somewhat rpm-dependent as certifugal forces tend to "stiffen" the rotor structure. Thus, it is common practice to display the structural dynamics characteristics of the wind turbine rotor on a plot of frequency vs. rotational speed (see Figure 15). On such a plot (termed a Campbell Diagram) radial lines from the origin represent nondimensional excitation frequencies of one-per-revolution (1P), twice-per-revolution (2P), etc. The intersections of these excitation rays and the resonant frequency lines indicate regions of possibly dangerous

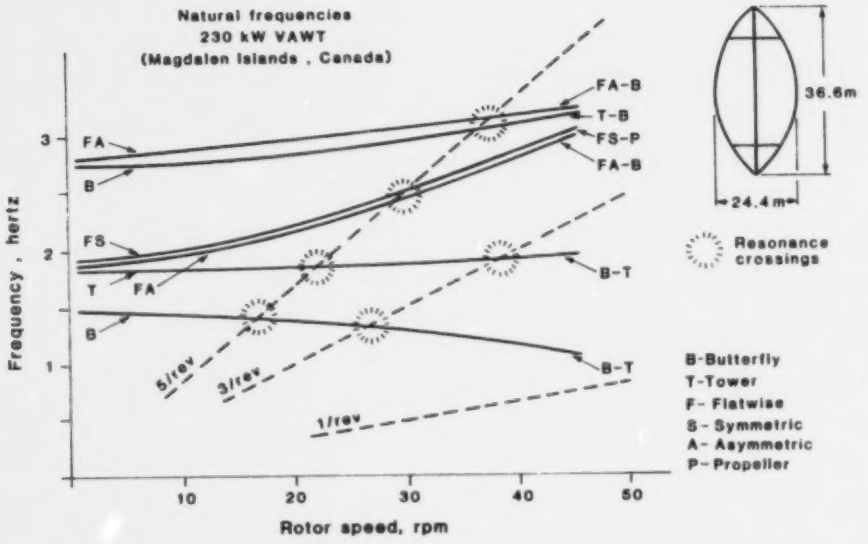

Figure 15. Campbell diagram showing structural dynamic characteristics of a VAWT (from reference E-20)

vibration. The energy transfer from the exciting force into the structure is not equal for all resonant crossings, therefore not all intersections on the Campbell Diagram are necessarily dangerous or fatigue life limiting. A combination of analyses, experience, and judgement is required for the designer to distinguish between the intersections of real concern and those of only academic interest. The final design must set operating speed away from harmful resonant crossings, but must also recognise the likely need to pass through potentially harmful resonances during start-up and shut-down.

The additional jeopardy and complexity of variable-speed operation can be clearly visualized from the Campbell Diagram. Rather than a single vertical line defining discrete 1P, 2P, etc. excitation frequencies as with constant-speed operation, variable-speed operation creates a band of excitation frequencies at each harmonic, thus significantly increasing the likelihood of approaching a dangerous resonance. For this and other reasons most current WECS are constant-speed machines, especially those in grid-coupled applications.

Structural dynamic problems on high-solidity rotors tend to be of much less concern. Less flexible blades, much lower rpm and stressing, and generally more rugged construction combine to reduce, but not eliminate, structural dynamic problems on traditional water pumping windmills and their like.

In addition to the steady, cyclic, and resonant stresses imposed on wind turbine components, the designer must also account for the environment in

which his machine may be installed. The corrosive effects of marine environments as well as the fatigue characteristics may play an important part in the selection of materials and fabrication processes. Additional drag and gravitational forces caused by ice accretions must be accounted for in coastal and northern installations. Nationally agreed design load cases for Canadian WECS are published by the Canadian Standards Association in reference E-9 (see also Section 6.4).

4.3.4 Control and Protection Techniques

The purpose of a WECS control system is to maximize energy output while confining operation within acceptable limits of engineering and environmental conditions. All WECS must be provided with means of limiting power output under occasional very high winds, in order not to overload the drivetrain and final energy conversion device. Three methods are in common use: furling, variable geometry, and aerodynamic stalling. All methods essentially decrease rotor efficiency to maintain output power within prescribed limits.

Most windpumps and several small electrical HAWTs use furling to limit power. This technique involves sensing abnormally high wind and progressively turning the rotor plane away from being perpendicular to the wind. The mechanism for achieving this purposeful "yaw error" is often incorporated into the tower-top machinery design so asymmetric aerodynamic forces, acting against springs or counterweights, cause the rotor to gradually furl above some "rated" wind speed and to become fully furled (parallel to the wind) at cut-out. Such systems automatically unfurl the rotor when wind speed decreases to within operating limits. Note that because of their directional symmetry, VAWTs cannot generally utilize this control technique, i.e., the VAWT rotor cannot be "yawed out of the wind".

Many large HAWTs are equipped with mechanisms which allow the pitch of the blades to be adjusted during operation. During start-up, blade pitch is adjusted to maximize torque at zero rotor speed and in low winds. During normal operation blade pitch is adjusted to optimize efficiency and thereby maximize energy output. At high wind speeds blade pitch is adjusted to maintain rated power, i.e., to give less than peak efficiency so as not to overload drivetrain components. Such blade pitch adjustments can also be made on straight-blade vertical axis rotors but are difficult if not impossible to achieve on curved-blade VAWTs.

To generate power, most WECS blades create "lift" by establishing flow patterns around the airfoil surface, in the same way that an airplane wing works. If the angle of attack of the flow approaching the airfoil exceeds a certain value, the flow detaches from the blade surface and the airfoil

"stalls" aerodynamically, with accompanying loss of lift or power. The phenomenon can be used to limit power of both VAWTs and HAWTs, especially those which operate at constant rpm, such as grid-coupled generators. By correct choice of airfoil and operating speed, increase in wind speed beyond a certain value alters the flow angle relative to the blade and part of the blade will "stall". In curved-blade Darrieus VAWTs the stalled part of the blade progresses from both ends near the column towards the equator. In HAWTs, stall proceeds from the hub towards the tip as wind speed increases above the "rated" value. Though not as precise in maintaining constant rated power as, for example, the pitch control system, aerodynamic stall control has the advantage of not requiring variable geometry components and accelerator systems on the rotor.

In addition to power limiting, the electrical WECS control system must maintain frequency and voltage compatibility with the network it is supplying. The simplest way of achieving this is to equip the WECS with an induction generator which locks onto grid frequency and maintains rotor rpm within a narrow range of synchronous speed as variations in wind speed significantly change WECS power output. Another advantage of the induction generator is that it can be used as a motor, drawing power from the grid, to start certain WECS in low winds. Electronic controls can be used to maintain grid compatibility using synchronous generators; their increased complexity is partially offset by their better power factor. Recently, ac-dc-ac power conversion equipment is being introduced to provide more flexible matching of WECS and network characteristics. Such "decoupling" allows variable rotor speed while maintaining constant frequency output and relieves the WECS designer of rpm constraints imposed by generator frequency characteristics. A case in point is Projet ÉOLE whose multipole generator is driven directly (without gearbox) by the VAWT rotor at speeds that are controlled to maximum system efficiency at high wind speeds. Despite its 162 poles the very low speed 3600-V ÉOLE generator produces power at between about 10 and 20 Hz depending on rotor and wind speed. This electrical power is rectified to dc and inverted back to grid-compatible 60-Hz ac at unity power factor. Such Static Frequency Converter equipment is becoming more readily available and at attractive costs relative to alternative WECS control and power conversion equipment. IREQ has conducted extensive tests on a similar SFC system at its 50-kW VAWT test installation at Varennes, Quebec.

Many electrical WECS are equipped with anemometers which start and connect the unit to the grid when wind speed exceeds cut-in. The same anemometers can also be used to detect cut-out wind speed and shut down the WECS.

The WECS control system must also detect and protect the machine from operational and environmental conditions beyond the design and/or safety

limits. Many potential malfunctions (such as loss of load, incorrect pitch adjustment, brake failure, etc.) ultimately manifest themselves as rotor overspeed which, if unchecked, may result in catastrophic failure. Thus many WECS controls use more than one level of overspeed protection. For example, EOLE uses four levels of overspeed protection; if speed rises above preset value:

- the SFC demands more output be provided to the grid, then
- the generator output is applied across a slave resistor, and/or
- aerobrakes are deployed to prohibit power generation by the blades and to substantially increase aerodymanic drag on the rotor, and finally,
- a twin disk six-caliper mechanical brake is applied.

Production machines seldom can afford the luxury of four independent overspeed protection systems; thus, the most expensive and least reliable subsystems are often omitted. Emergency braking systems are sometimes fitted temporarily to prototype units to provide protection until the reliability and effectiveness of the production system is proven. On Indal Technologies 50 and 500-kW VAWTs, the gravity-applied bullgear-brake has proven so reliable that aerobrakes and regenerative braking systems are not required on production versions. In some WECS configurations overspeed protection is incorporated by designing the rotor and drivetrain to withstand maximum run-away speed. As discussed in Section 4.3.1, high-solidity rotors have relatively modest free-running rpm even in high winds. For such configurations it may be more cost-effective to design the rotor to withstand the high centrifugal loads than to equip the machine with means of detecting and controlling overspeed.

The transient behaviour of wind turbine controls is important, both to maintain control during gusty or turbulent winds and also to prevent out-of-limits operation during switching or during malfunctions of the energy network to which the WECS is connected. A 500-kW VAWT prototype was destroyed because its control system was unable to resolve a momentary loss of line power during a starting sequence in high winds.

As with all mechanical systems, WECS (especially large-scale WECS) must be equipped with monitoring sensors that detect malfunctions, hopefully before they cause catastrophic failures. Commonplace vibrations sensors, bearing temperature monitors, loss of vital fluid pressures, etc., can be arranged to trigger preventive shutdown and/or diagnostic routines. On large HAWTs the blades are sometimes pressurized internally so that loss of such pressure may signal a crack long before critical loss of strength occurs. One

Danish manufacturer used a simple ball bearing sitting on a microswitch to detect out-of-balance or significant asymmetric rotor loads - the tower shakes, the bearing falls off the microswitch, and the control system shuts down the turbine.

Windpump control systems are usually very simple, often comprising little more than the furling mechanism. Attempts by DELTX to maximize energy capture of their 16-m delta-blade rotor have resulted in a hydro-mechanical controller that varies pump stroke to maintain tip speed ratio near the value for optimum efficiency over a broad range of wind speeds. It is generally thought that the added complexity is only justified for large machines. Windpumps used for drainage and some irrigation applications must be designed to self-protect if the well runs dry (and hence there is no restraining load) at all wind speeds.

Controls for WECS used in wind/diesel hybrid powerplants have to be integrated with the diesel-generator governor and must account for the highly variable nature of the WECS power output caused by wind speed variations. Testing in Canada has not indicated premature failure or excessive maintenance requirements for the diesel governor trying to regulate and gap-fill between relatively stable power demands and rapidly fluctuating WECS output. However, operating experience to date has not been extensive and current projects (e.g., Winisk, Fort Severn, Fort Chimo) may shed more light on this matter.

5.0 NATIONAL RESEARCH COUNCIL EXPERIMENTAL AND ANALYTICAL RESEARCH

Wind Energy research at the National Research Council began several years before the oil crisis of 1973, which forced the industrialized nations to give urgent attention to the development of renewable sources of energy. As mentioned in the Introduction, in 1966 two aerodynamicists, P. South and R.S. Rangi of the Low Speed Aerodynamics Laboratory, re-invented the fixed-geometry vertical axis wind turbine that is now known as the Darrieus rotor, after G.J.M. Darrieus who had invented it in France about 40 years earlier. The following paragraphs summarize the subsequent laboratory research, both experimental and analytical, that formed the basis for later program expansion and for VAWT development by Canadian industry.

In particular, the three-year period beginning in 1973 was one of intense activity by a team of only two to three researchers, and it was possible to publish summary papers in 1976 that described preliminary solutions to the problems of aerodynamic design and configuration optimization, avoidance of blade flutter and rotor collapse in high winds with ice loading included, the design of aerobrakes, the use of structural damping to reduce resonant stress levels, and the performance of constant-speed grid-coupled turbines with high grid penetration. Other accomplishments in the same time period included the use of Savonius rotors on the central rotor column to improve self-starting, the first analytical estimate of the limits to spacing of turbines in very large arrays, and the first wind energy resource maps of Canada. It was a productive period, and when the official government wind energy research and development (WERD) program was set up in 1975 a basic foundation had already been laid for VAWT technology development.

5.1 Experimental Investigations

5.1.1 Vertical Axis Wind Turbine Performance

In 1966 South and Rangi carried out basic wind tunnel tests of two small VAWT rotors, about 0.76 m in diameter. The first had three straight blades and although it confirmed that a fixed pitch rotor with symmetric airfoils would auto-rotate and produce power, it proved to be structurally unacceptable because of the large centrifugal bending moments in the blades. The second rotor had blades curved in the shape of a skipping rope to eliminate centrifugal bending moments, and it was tested with two, three, four, and six blades. The results of the curved-blade tunnel tests were published in 1971 in reference A-1. When corrections were made for the small scale of the models, it was indicated that the maximum aerodynamic efficiency could be comparable with that of the best modern HAWT.

Wind energy research had a low priority at that time and little further work was done until a new large (9 m × 9 m) wind tunnel was commissioned at

NRC in the early 1970's. This provided an opportunity to test the first Darrieus rotor of significant scale (4.27-m diameter), and the results, published in 1972 (A-2), confirmed that high efficiencies could be achieved at high values of the blade-to-wind speed ratio. Specifically, a maximum power coefficient (see definition in Section 4.3.1) of 0.37 was reached at a tip speed ratio around 6:1.

Subsequent tests in the 9 m × 9 m wind tunnel with a rotor of diameter 3.66 m, having three blades or a single counter-balanced blade, investigated the use of an external supporting frame for the rotor, the use of aerobrakes and the effect of total blade area (or solidity) on the performance characteristics (A-6).

By 1975 it had become apparent, from wind tunnel measurements and by agreement with the first theoretical developments (see Section 5.2.1), that the aerodynamic performance of the Darrieus VAWT was well enough understood for design purposes, and the laboratory research emphasis had already been shifted to the solution of other problems.

5.1.2 *Grid Coupling*

At low ratios of blade speed to wind speed (say below about 3:1) the aerodynamic angle of attack of the blades of a VAWT or HAWT begins to exceed the angle at which airfoils will stall, i.e., the flow past the airfoils becomes detached from the suction side. Rotor efficiency and shaft torque begin to fall rapidly. One consequence is that rotors with low solidity (i.e., narrow blades of relatively small area), which have high efficiency at high rotational speed, also have low starting torque. This, of course, is a disadvantage in wind turbines designed for "stand-alone" operation where aerodynamic self-starting is a desirable feature. However, this characteristic can be turned to good advantage in the design of turbines that are to be electrically connected to an existing ac power system.

It was recognized early in the NRC research program that progressive aerodynamic stalling could be used to limit the maximum power output of a Darrieus turbine in high winds, if the turbine rotational speed was held constant, or nearly constant, because as wind speed increased the blade angle of attack would oscillate cyclically to higher amplitudes and eventually beyond the stalling angle. Nearly constant rotational speed could be achieved by coupling the turbine to an ac power system through either a synchronous generator or an induction motor/generator. In the latter case there is a small "slip" between shaft speed and the ac synchronous field rotational speed, but the alternator will operate either as a motor or a generator depending on the torque load on its shaft. The rotor may then be started and brought up to operating speed simply by closing the circuit to

the power system. The fact that the aerodynamic starting torque is low is an advantage in this case because it can be overcome by a brake of modest capacity until electric starting is inititated by the turbine control system.

The first operation of a Darrieus turbine in the "grid-coupled" mode took place in 1973, in which a 3.66-m diameter turbine, operating on the roof of the laboratory building was electrically connected to the 110-V, 60-Hz mains through a commercial single-phase induction motor that operated in the generator mode when wind speed was sufficiently high. Since that time almost all Darrieus turbines that have operated in the grid-feeding application throughout the world have been of this general type, using three-phase induction generators and aerodynamic stall control for limiting power output in high winds. The 4-MW ÉOLE system (Section 7.9) will be different; its generator is of the synchronous type, coupled to the grid through an ac-dc-ac link to allow variable-speed operation.

The principle of stall control of constant-speed wind turbines had been used previously by designers of HAWT rotors, particularly in Denmark. Many of that country's most successful commercial turbines are grid-coupled through induction alternators and have three-bladed horizontal axis rotors with fixed-pitch blades. The simplicity of this concept is partly counteracted by a loss in overall efficiency since a fixed geometry rotor running at constant speed will be at its best aerodynamic efficiency at only one wind speed. However, calculations show that the overall penalty in energy production is only about 10% or less (for HAWTs or VAWTs), and since the simplification of the system may easily give more that 10% improvement in costs and reliability, the penalty is usually worth taking.

5.1.3 Rotor Structural Dynamics and Aeroelasticity

From the beginning of the VAWT research program it was clear that fatigue of rotor blade materials was a potentially serious problem, since both the chordwise and flatwise components of aerodynamic loading on the blades are cyclic and contain large-amplitude harmonics of rotor rotational frequency. There were also questions of structural stability such as the compressive collapse of curved blades in high winds when the rotor is stopped, and the possibility of aeroelastic instability or blade flutter when operating. Flutter had in fact been discovered accidentally by the Sandia Laboratories in about 1974 while carrying out wind tunnel tests of a small Darrieus rotor with wooden blades.

The National Research Council Low Speed Aerodynamics Laboratory lacked the resources at that time to carry out elaborate theoretical analysis of these dynamic problems. On the other hand it was fortunate in possessing an

excellent range of low-speed wind tunnel facilities and the expertise required to adapt experimental techniques that had long been used for other aeroelastic investigations in wind tunnels. Accordingly, a series of rotor models was tested that ranged in height from about 0.15 to 9 m.

The smallest models were nonrotating models with blades made from flat metal shim stock. They were tested in a 1 m × 1 m low-speed tunnel with different orientations relative to the wind direction to determine the most critical conditions for blade collapse in high winds. Not surprisingly, this was discovered to occur on the upwind blade when the blade presented its flat surface to the wind; but it was also discovered that a pair of horizontal struts extending from blade to blade across the central column of a two-bladed rotor could approximately double the wind speed required to produce blade collapse. The form of dimensional analysis used in reducing the results of these model tests made it possible to account for gravity effects on blade stability and thus to estimate the effects of the weight of accumulated ice on the wind-induced collapse of blades of any given initial weight.

By early 1975 it had been decided to proceed with the construction of a large Darrieus VAWT, which was eventually installed on the Iles de la Madeleine in the Gulf of St. Lawrence, and it was necessary to investigate its structural dynamic characteristics. A 1/24-scale rotor model of 1.5-m height was built with detachable blades of different widths, thicknesses, and materials, to investigate the conditions leading to blade flutter. The tests were carried out in the NRC 2 m × 3 m wind tunnel and dimensional analysis was again used to generalize the results. There were several important findings. The critical rotational speed at which flutter began was found to be nearly independent of wind speed and could be approximately doubled by the use of the same kind of horizontal bracing struts as those found to be effective in stiffening the blades of a parked rotor against collapse in high winds. Moreover, it was discovered that, contrary to the case of flutter of aircraft wings or helicopter blades, the relative location of the blade chordwise center of mass and torsional center was unimportant. This greatly widened the scope for methods of blade construction and confirmed the feasibility of using hollow aluminum airfoil extrusions, a low-cost innovation that had already been pioneered by Indal Technologies Inc. (then known as Dominion Aluminum Fabricating Ltd.)

In mid-1975 a 1/4-scale aeroelastic model (9 m high by 6 m diameter) of the Iles de la Madeleine rotor was tested in the 9 m × 9 m wind tunnel to investigate other structural dynamic problems, especially those associated with resonant frequencies that could be excited by harmonics of the blade aerodynamic loads. It was found that a potentially dangerous resonant condition was the so-called "butterfly" mode, in which opposite blades of a

two-bladed rotor oscillate about their equilibrium plane like the wings of a butterfly. When the natural frequency of this mode happens to be an odd multiple (1, 3, 5, etc.) of the rotor rotational frequency, large stress amplitudes may be induced by the cyclic aerodynamic loads. Accordingly, a damping system at the attachment of the cross-struts with the central rotor column was devised and built into the full-scale turbine. Subsequent field trials, however, indicated that damping systems of this type may add to maintenance problems and that structural resonance can be avoided in other ways.

Theoretical methods for carrying out detailed rotor structural dynamic analysis were not developed beyond preliminary stages at the National Research Council, since the experimental projects had provided the design information that was needed initially, and also because it was known that analytical methods were under development at the Sandia Laboratories in the United States. As a part of the close international relationship that had developed between the laboratories during early VAWT development, the Sandia dynamic response program, known by the code name FFEVD, was generously made available to Canadian users (A-19, F-16).

5.1.4 Aerobrakes

The reliability of commercial production models of vertical axis wind turbines, including their mechanical brakes and control systems, has achieved a level such that uncontrolled rotor overspeed episodes are extremely unlikely to occur. However, that is not necessarily the case with experimental prototypes. In the early phases of Canadian VAWT development, almost all rotors were fitted with some sort of self-actuating aerobrakes installed on the blades, usually near the rotor equator. It was found in early NRC wind tunnel tests (A-6) that, if these took the form of flat plates that opened so that the plane of the plates, which were hinged at the blade trailing edges, was approximately at right angles to the blade airfoil chord plane, their drag was sufficient to negate the rotor torque even if the total aerobrake area were only of the order of 1% of the rotor swept area. They could effectively bring a free-wheeling rotor down to a relatively low rotation rate under almost all wind conditions. It was later found possible to collapse all of the measured flat-plate aerobrake data to a single design curve (A-10).

The early flat-plate aerobrakes had one limitation: as rotor speed is reduced relative to wind speed, the blade airfoils begin to pass in and out of the stalled condition during each revolution. When stalled, the flow detaches from one side of the blade, and one half of an open aerobrake at the trailing edge may be immersed in the turbulent wake. Thus the aerobrakes may lose approximately half their effectiveness during a large part

of the rotor rotation. In practice, it has been found that a free-wheeling rotor with this simple type of aerobrake in action will continue to rotate at an equilibrium speed such that the equatorial blade speed is roughly equal to the wind speed. While this will generally be much lower than the normal operating speed, it is likely to be unacceptable in the event of loss of load or of control at high wind speeds.

When it was later decided that aerobrakes should be installed as an extra safety measurement on the prototype Projet ÉOLE 4-MW rotor, further wind tunnel tests were carried out at NRC on alternative aerobrake configurations. One of these had been suggested by Canadair Ltd., which had played a part in the early stages of ÉOLE rotor design, and it had proved to be more effective in producing high drag throughout the stalled condition. It took the form of drag plates, hinged to open on both sides of the airfoil about the trailing edge, and thus resembled the earlier simple flat plate configurations; the important difference was that, when open, a large gap, which they covered when closed, was also opened immediately ahead of them, through which a strong flow of air developed from the pressure side of the airfoil to the suction side at high angles of attack. The results of the wind tunnel tests are reported in reference A-55.

5.1.5 Static and Dynamic Airfoil Characteristics

A further need for aerodynamic data arose in the preliminary design phase of Projet ÉOLE. On the basis of experience with smaller VAWT rotors it had been decided to adopt the NACA 0018 airfoil for the blade sections, but there was a lack of appropriate data on the sectional values of lift and drag over the complete range of angle of attack (±180°) with which the blades have to operate on a VAWT, and because of the large physical size of ÉOLE (blade chord = 2.4 m), the airfoil Reynolds number spanned an unusually large range, up to approximately 10 million. The NRC wind tunnel that has the highest available Reynolds number for two-dimensional airfoil tests is not the largest wind tunnel, but rather the 1.5 m × 1.5 m blowdown tunnel, which can operate with internal pressures up to about 10 atm at subsonic speeds. In late 1982 a model NACA 0018 airfoil, having a chord length of 0.25 m, was tested over a wide range of conditions in the 1.5-m wind tunnel, and a condensation of the resulting data is given in reference A-40. These data have also been loaded into the NRC computer codes, as one of the choices available for the the computation of VAWT performance and aerodynamic loads.

During early VAWT field tests of constant-speed turbines in Canada and the United States it was discovered that, although blade stalling did at least partially level off the maximum power at high wind speeds, the level was

substantially higher than had been predicted with the available theories. Although at first this might be thought to have been a welcome discrepancy, it was in fact an embarrassment because of the danger of overloading the power train. Adjustments could be made by reducing the rotor speed, i.e., by an appropriate change in the gearbox ratio between the rotor and the alternator, but there was little or no gain in overall energy output. At about the same time a somewhat similar phenomenon was turning up on the type of stall-controlled, constant-speed horizontal axis turbines being developed especially by Danish firms. It was considered the phenomenon known as dynamic stall, familiar to the designers of fixed-wing aircraft and helicopters, was probably responsible. Dynamic stall results from a delay in the flow around an airfoil to fully develop in response to rapid changes in angle of attack and thus, for example, the blade lift may go on increasing well beyond its normal maximum value if the angle of attack is increasing rapidly as it passes through the static stall value. Since the shaft torque of a VAWT is largely the result of the forward component of blade lift, an overshoot in maximum torque can occur.

In order to allow for this effect in VAWT performance prediction, the Sandia laboratories adapted a method that had been developed for the numerical simulation of dynamic stall in helicopter blades (where the blade angle of attack also varies rapidly during each revolution), but it was recognized that the angle of attack history for a VAWT blade is very different from that of a helicopter blade. Accordingly, an experimental investigation was conducted in the NRC 2 m × 3 m low-speed wind tunnel, using an oscillating NACA 0018 airfoil, to determine the dynamic stall characteristics over the angle of attack range appropriate to a partially stalled VAWT rotor. The results have been published in reference A-54, and have been used at NRC to modify the helicopter empirical model used in the computer programs. Nevertheless, the question of the effect of dynamic stall on the aerodynamics of VAWT and HAWT rotors remains in a somewhat unsatisfactory state. The phenomenon is probably different for the two main rotor types, and in any case the use of adjusted empirical models without a suitable framework of fluid dynamic theory leaves doubts as to the generality of the models. No doubt future research in other countries will improve this situation.

5.2 Analytical Methods

5.2.1 VAWT Performance Prediction

As part of the concentrated effort, beginning in about 1973, to more fully understand the performance characteristics of the Darrieus VAWT and to provide means for calculating aerodynamic structural loads and for the design of rotors for optimum performance, theoretical methods of analysis were developed in parallel with the NRC Low Speed Aerodynamics Laboratory experimental program summarized previously.

The first aerodynamic theory for predicting the performance of the curved-blade VAWT rotor was published in June 1974 (A-5). It was an adaptation of the classical momentum theories of Betz and Glauert, developed in the first quarter of the century for the simple single-disk horizontal axis rotor, and as such it retained some of the same basic assumptions. For example, it was assumed that the reduction in wind speed as it passes thro[illegible]e rotor (the so-called induced velocity) is uniform over the entire cross section of a single "actuator disk" representing the rotor and is related to the rotor drag force in the wind direction. It was recognized that, particularly for a rotor so different from the single-disk horizontal axis type, this would be a crude assumption but, as the reference states, "although refinements that allow for non-uniform velocities may be possible without much additional computational complexity, the assumption of uniform induced velocity avoids the necessity for interactive calculations." Somewhat surprisingly, after reasonably large-scale tests had been completed on aerodynamically clean rotors in the NRC 9-m wind tunnel, good agreement was found between the measured performance and the prediction of this simple theory (A-9). It has formed the basis for all of the more refined momentum theories of the Darrieus rotor that have been developed since that time.

The Sandia Laboratories were the first to develop the "multiple stream tube" refinement (F-13), which still retained the single-disk assumption and therefore did not allow for differences in velocity and loading on the upwind and downwind rotor faces, but which did permit the calculation of the effects of wind shear or other non-uniform wind conditions. Eventually the next obvious refinement to the momentum method was made by several investigators: the "double multiple stream tube theory", which separately dealt with the two faces of the rotor and allowed for the change in induced velocity behind the upwind face. The NRC version was developed in 1979 (A-43). The computer codes include the empirical dynamic stall correction referred to in Section 5.1.5, but at the option of the user.

5.2.2 Wind Turbine Spacing in Large Arrays

When it had become apparent in the early days of the Canadian R&D program that grid-coupled wind turbines offered a means of contributing significantly to the electricity supply of large- or small-scale power networks, the Low Speed Aerodynamics Laboratory began a study of the availability of wind energy as a natural resource. In a country as large and geographically diverse as Canada, two questions immediately arise: what is the distribution of average wind speeds (and hence average wind energy density) in all regions, and in any given wind area how much of the energy is really available? The first of these questions is discussed in Section 3.3.3 and a recent energy density map of Canada is shown in Figure 8.

The answer to the second question depends on how closely wind turbines may be spaced in extensive arrays, before their mutual interference (due to de-energizing the local wind field) begins to limit their output. A preliminary literature search failed to disclose any relevant information, either theoretical or experimental. A theoretical study was undertaken in the laboratory, in which it was assumed that an indefinitely large array of wind turbines would affect the surface wind boundary layer as if an additional coarse but sparse roughness had been added to the roughness already present on the terrain. The conclusion was that, although the maximum energy extraction per square kilometre or per square mile of terrain would occur when turbine spacing was between about 5 to 10 rotor diameters, the energy produced **per turbine** would begin to decrease rapidly if they were spaced closer than about 30 diameters. This conservative value was used in the production of the first wind energy map of Canada (A-4), which indicated that in the windiest regions, which were in eastern and northern coastal area and in the southern prairies, the average power production could be of the order of 400 kW per square mile terrain surface area. While at first this may not seem an impressive figure, it is in fact larger than the hydro power potential per square mile of watershed area of typical large Canadian river systems.

The results of the theoretical study of wind turbine spacing were published in a laboratory report (A-7), and it appears to have been the first paper ever published on the subject. It was not, however, the last. As other countries began to consider large-scale "wind farms" either on land or in shallow off-shore water, the spacing problem received concentrated study. The NRC theory dealt only with the extreme case of an indefinitely large array, and as might be expected, later studies have indicated that in relatively small arrays, permissible spacing may be as low as 5 to 10 diameters with no more than 10% loss of output per turbine. The problem became the subject of two collaborative tasks under the Wind Energy R&D Executive Committee of the International Energy Agency and a final report was issued in 1984 (D-49).

There is still a paucity of measured data on the aerodynamic interaction of wind turbines in small or large arrays, but another cooperative IEA task is investigating turbine wakes; other related work is believed to be in progress with some of the large wind farms in California.

5.2.3 Fatigue Life Prediction

Horizontal and vertical axis wind turbines are both subject to fatigue damage or failure owing to the cyclic nature of their blade loading, but the basic causes are different in the two cases. In the large-scale HAWT, cyclic blade edgewise strains are dominated by gravity at a frequency of once

per revolution. There are also flapwise cyclic bending strains due to wind shear (the variation of average wind speed with height above ground level) through which each blade sweeps during a revolution. In the Darrieus VAWT, however, the main cyclic blade loads result from the variation of blade angle of attack during rotor rotation. Although the largest aerodynamic load amplitudes are those in the blade flatwise direction, tending to push the blade toward the rotation axis on the upwind side of the rotor and to pull it outward on the downwind side, this load component does not generally induce large blade bending moments. The reason is that the spanwise distribution of the aerodynamic load is not radically different from the centrifugal load, which the curved blade shape is designed to minimize. However, large leading and trailing edge blade strains are induced by the cyclic edgewise or chordwise blade thrust force, which is the rotor driving force, and which reaches a maximum value twice during each revolution. The few Darrieus blade failures that have occurred have been the result either of gross rotor overspeed or blade edgewise fatigue.

On 15 November 1985 the 500-kW Project Aquilo turbine (see Section 7.6) suffered a blade failure, later diagnosed (A-20) as being due to edgewise bending fatigue possibly hastened by corrosion in the marine environment in which it had operated for two years. A subsequent fatigue analysis, based on strain histories measured at a blade location near the fatigue crack location indeed indicated a short fatigue life. The data indicated something else as well: the cumulative fatigue damage was probably increased significantly by turbulent fluctuations of the site wind speed. The effect is difficult to estimate since obviously the turbulence of natural winds cannot be turned on and off at will during testing. However, an approximation to the nonturbulent strain histories was made by averaging them over several rotor revolutions at each wind speed. Stress ranges were then counted for the actual recorded samples and for the reconstructed "nonturbulent" cases, using the so-called rainflow counting alogorithm, and fatigue life was then estimated, taking into account the relative frequencies of different wind speeds.

The result in this case was an apparent reduction in fatigue life by a factor of about three, due to turbulence. The extreme sensitivity of fatigue life to atmospheric turbulence appears to have been recognized relatively recently and has also been found in a similar analysis of strain data from a horizontal axis turbine (F-17).

In order that, in future, fatigue life estimates may be carried out as soon as possible during wind turbine field trials, the NRC high-speed data acquisition system has had additions made to its software to permit on-line rainflow cycle counting of strain data, which are then accumulated in files. A cumulative fatigue damage computation routine is also included,

which permits fatigue life to be estimated for specified wind conditions, using stored fatigue test data for the structural material used in the relevant rotor component. This system will be used, for example, during early field testing of the 4-MW Projet ÉOLE.

6.0 TESTING AND STANDARDS

6.1 The Atlantic Wind Test Site

Early experimental work with wind tunnel and roof-top model WECS at NRC confirmed the need for well-instrumented outdoor test facilities and established test procedures and standards. In 1980, as part of the enhanced federal energy R&D initiative, a federal/provincial agreement was signed to establish a national windmill testing facility at North Cape on Prince Edward Island (B-1). The site, contributed by the province, comprised a promontory of about 200 ha of flat cleared land well exposed to the winds and marine environment of the Gulf of St. Lawrence (see Figure 16). Tests on a 1:500 scale model of the site were performed in the LSAL/NAE 2 m × 3 m wind tunnel to explore flow patterns at the 16 test pad locations (B-17). Federal (EMR) capital funds provided for a laboratory/bunkhouse and a data acquisition system capable of monitoring 256 parameters per second. The

Figure 16. Atlantic wind test site

Atlantic Wind Test Site (AWTS) opened for business in June of 1981. Its facilities and capabilities are described in reference B-2.

The Atlantic Wind Test Site operations are supported by user fees and a 10-year contribution agreement with NRC. A board of Directors, chaired by NRC, monitors both technical and administrative management of the site, which is carried out by the Institute of Man and Resources, a nonprofit research institute in Charlottetown, P.E.I. Annual reports (B-3, B-9, B-10) are distributed to participants and others in the wind energy community.

To date AWTS has conducted over 20 wind energy research and development projects (B-11 to B-33). These have included performance and structural evaluations of experimental and preproduction prototype WECS, development of testing and instrumentation techniques, site assessments, and predeployment check-out of equipment destined for demonstration in remote Canadian communities. Staff of AWTS have participated in international joint projects to develop and assess WECS testing techniques and data processing methods. These projects have occasionally necessitated exchange of senior personnel between AWTS and its European counterparts.

Based on the growing experience of the staff, AWTS is becoming a major contributor to international WECS testing technology and a trusted source of impartial information and advice on Canadian utilization of wind energy. Its clients have included the NRC, federal and provincial government departments, WECS manufacturers and users, and the Canadian Standards Association.

Currently, AWTS has a permanent staff of five people with electrical, electronic, and mechanical engineering skills. In addition to continuing evaluation of five wind turbines ranging from 1 to 500 kW rated power, AWTS is preparing for a major program of work on wind/diesel powerplant systems to address near-term opportunities in the isolated (not grid-connected) communities along both coasts and in the northern parts of Canada.

6.2 The Lethbridge Windpump Test Station

In 1982, the Drainage Branch of Alberta Agriculture, in conjunction with Jensen Engineering and the Alberta Research Council, established the Windpump Test Station near Lethbridge, Alberta, in order to evaluate and demonstrate the potential of using wind turbines for pumping water in agricultural applications. Funding was provided by Farming of the Future, the Alberta/Canada Energy Resources Research Fund, Alberta Agriculture, and TransAlta Utilities. Since its initiation, the site has generated considerable interest in utilizing wind turbines throughout Alberta and western Canada (see Figure 17).

Figure 17. Lethbridge windpump test station.

The Test Station evaluates experimental, prototype, and production model windpumps provided by manufacturers or distributors. No charge is made for the tests, or for the reports which are freely available to the general public. The test results are reported in a standardized format denoting cut-in and cut-out speeds, pumping characteristics, maintenance requirements, and general survivability. Also presented are calculated monthly water delivery volumes for four specific sites representative of typical areas in the western Canadian prairies. In addition to obtaining the quantitative data, the Lethbridge Test Station encourages potential users to visit the site and observe the machines under test (F-4). Interest in the site has been shown nationally as well as internationally. Manufacturers from the United States and Europe have expressed desires to bring wind turbines to this area for testing and possible sale.

The Test Station publishes an annual report (F-4) summarizing the tests conducted and the plans for the following year. Eight windpumps, one

photovoltaic pump, and one electricity generating windmill had been evaluated as of the end of 1985. In addition to six more windpumps scheduled for test in the summer of 1986, arrangements have been made to test one Canadian and one British design during the winter of 1985/86, using calcium chloride antifreeze in the pumping loop.

6.3 International Meeting of Test Stations for Small Wind Energy Conversion Systems

During the early 1980's, several countries established test stations for research and evaluation of wind energy systems. As these institutions were dealing with new technology, both in respect to the equipment being tested and in respect to the testing techniques themselves, there were clearly significant benefits to be shared by effective exchange of experience among national test stations. The first International Meeting of Test Stations for SWECS (IMTSS) was hosted by the Danish facility at RISØ. Subsequent annual meetings have been held as listed in Table 8. Proceedings of these meetings are available from the host national test station.

Currently, the national WECS testing facilities of 15 countries are members of IMTSS (see Table 9), and three new members are expected to join in 1986. Chairmanship rotates annually to the manager of the facility hosting the annual meeting.

Major topics of discussion within IMTSS have included

- selection of parameters for performance and functional testing of WECS
- sensors, signal conditioning, and data acquisition systems
- accurate measurement of wind regime characteristics
- structural testing of WECS systems and components

Table 8. Meetings of IMTSS

Date	Locale/Test Site Host	Country
9/10 November 1981	ECN Windturbine Testveld, Petten,	Netherlands
17/18 September 1982	Riso Test Station for Windmills,	Denmark
3/4 May 1983	GKSS Vindtestfeld, Pellworm,	Germany
25 May 1984	Centre National d'Essais Eoliens de Lannion,	France
24 October 1984	EWEC Conference, Humburg,	Germany
21/23 August 1985	Atlantic Wind Test Site, P.E.I.	Canada
(2/3 October 1986)	DFVLR Vindtestfeld, Schnittlingen,	Germany

Table 9. Membership of IMTSS (31/12/85)

Country	Agency/Test Station
Austria	
Belgium	Vrije Universiteit Brussel, Windenergie Testveld, Laarbeeklaan
Canada	Atlantic Wind Test Site, PEI
	Lethbridge Windpump Test Site, Lethbridge
China	North-Chino Electric Power Test and Research Institute, Beijing
Denmark	RISO Test Station for Windmills
France	Centre National d'Essais Eoliens de Lannion
Germany	DFVLR - Windtestfeld, Schnittlingen
	GKSS - Windtestfeld, Pellworm
Greece	Public Power Corporation, Athens
Italy	ENEL Santa Caterina WECS Test Station
Ireland	National Board for Science & Technology, Dublin
Netherlands	ECN Windturbine Testveld, Petten
Spain	Programa Energetico UNESA-INI, Palma de Mallorca
Sweden	The Test Station for Small Windmills, Chalmers University, Goteborg
United Kingdom	National Engineering Laboratory, East Kilbride, Scotland
	Rutherford Appleton Laboratory, Oxford
United States	Rocky Flats Wind Turbine Test Center, Golden, Colorado
	Sandia National Laboratories, Alberquerque, New Mexico
	USDA Agricultural Research Service, Bushland, Texas

- assessment and harmonization of national and international standards
- statistical, data processing, and reporting requirements for WECS performance testing
- design standards and licencing criteria

Recent IMTSS meetings have included presentation of technical papers concerned with new instrumentation techniques and equipment and with analysis methods for interpreting and presenting performance and structural data from experimental systems.

6.4 Canadian Standards Association Standards and Guidelines

In August 1981 NRC tasked the Canadian Standards Association (CSA) to advise on the structure and content of design, safety, testing, and siting standards for small wind energy conversion systems (SWECS) up to 100 kW maximum power rating. The purpose of such standards was to assure purchasers that qualified equipment was designed to withstand realistic environmental and operational conditions, and, for grid-coupled SWECS, that safe interconnection could be made to Canadian electricity networks. For Canadian SWECS manufacturers, the standards would provide a universal and

objective measure of capability in both domestic and international markets. Also, the existance of recognized national standards provides a basis for acceptance by financial, insurance, and other institutions.

In March 1983 NRC contracted with CSA to develop the SWECS standards by mutual concensus among technical subcommittees comprising representatives of users, manufacturers, technical specialists, and consumers. In addition, representatives of the American Wind Energy Association (who were then developing similar standards in the United States) were also included within the CSA technical subcommittees. General consistency with other standards-setting groups in Europe was achieved through personal contacts, the IMTSS, and by Canadian participation in the International Standards Organization.

By March 1986 the following CSA Preliminary Standards had been issued:

F416-M1985: *SWECS Safety and Design Criteria* (E-9)

The purpose of this Standard is to specify design criteria for the safety of small wind energy conversion systems (SWECS) with rated mechanical power of 100 kW or less. These criteria apply to all types of machines that may extract electrical, mechanical, or thermal power from the wind.

Particular attention is paid to characteristics of the wind phenomena and ranges of design values appropriate to North America. The various modes of WECS operation and non-operation involving a different mix of environmental and loading parameters are also addressed.

F417-M1986: *WECS Performance* (E-10)

The purpose of this Standard is to specify performance criteria and test methods for wind energy conversion systems (WECS). These apply to all types of horizontal or vertical axis machines that may extract electrical, mechanical, or thermal power from the wind.

The test techniques and reporting formats described in this Standard were evaluated by the Atlantic Wind Test Site and the Lethbridge Windpump Test Station (B-34, F-5).

F418-M1986: *WECS Interconnection to the Electric Utility* (E-11)

This Standard provides guidance, not only to utilities and their customers who will be directly involved in the connection, but also to manufacturers of equipment used in the various arrangements and to

engineers who will design these systems. In this way, all those involved will be operating under a common set of requirements.

Acceptance of a WECS electrical system by a utility should not be viewed by a potential WECS owner/user as the seal of approval on the quality, reliability, or performance of the WECS. Rather, acceptance will indicate that the utility considers that the interconnection of the WECS will not adversely affect the safety, reliability, and quality of the utility service.

F428-M1986: *SWECS Siting Guidelines* (E-12)

These guidelines were prepared by AES/EC and are intended to provide information regarding the meteorological aspects of the siting of SWECS. Data are presented on the influences of nearby and distant topographical features and on wind-speed measuring techniques by which quantitative assessments of candidate locations can be made.

The Standards are available from

The Sales Group
Canadian Standards Association
178 Rexdale Boulevard
Rexdale, Ontario
Canada
M9W 1R3
(416) 747-4044, Telex: 06-989344

6.5 International Standards

The United States and many European nations are preparing WECS standards. Denmark has already instituted a procedure of formal licencing whereby manufacturers submit a sample of each WECS model for testing at RISØ, the Danish national WECS testing station (F-6). Approval is based on physical tests and review of design methods and load cases. A licence is mandatory for connection to the utility grid and for mortgage and insurance coverage for the installation.

The worldwide nature of the WECS market demands mutual recognition of national standards. Thus the IEA has prepared a number of Recommended Practices (see Section 2.6 and references D-51 to D-55) governing design criteria and performance assessment of WECS. These are used as major references in the preparation of most national standards, thus providing some inherent compatibility. The Canadian Preliminary Standards will be widely distributed among the international wind technology community to encourage both conformity and criticism.

7.0 FIELD TRIAL PROJECTS

7.1 Early Work at the National Research Council

The early Research and Development work at NRC was carried out with wind turbine models of the vertical axis design that were built in-house. These models, ranging from 0.76 to 4.27 m in diameter, were made in the workshop of the Low Speed Aerodynamics Laboratory (LSAL) and tested in the National Aeronautical Establishment 9 m × 9 m wind tunnel. Two of these models were installed and operated on the roof of the LSAL.

The wind tunnel tests, see Section 5.1, had shown that the vertical axis wind turbine had a power coefficient comparable with the horizontal wind turbine. Researchers at NRC were convinced that the VAWT design, due to its simplicity, had the potential to be more economical than the horizontal axis wind turbine. It was therefore decided to start the transfer of VAWT technology to the industry.

7.2 Initiation of Industry Involvement

During 1973 it was concluded that the VAWT development at NRC had reached a stage where it could be transferred to industry.

A Request for Proposal for the supply of six 1-kW dc autonomous units was sent to a number of companies in early 1974. The competition was won by Dominion Aluminium Fabricating Ltd. (DAF) of Mississauga, Ontario, later renamed Indal Technologies Inc. DAF went on to produce a number of VAWTs with power ratings of 5, 50, 224, and 500 kW.

In 1979 Bristol Aerospace of Winnipeg, Manitoba, also built a number of small VAWTs with direct-drive dc generators with rated power ranging from 1 to 5 kW. Six units were developed and operated periodically for several years. Adecon Energy Systems Ltd. of Toronto started up in 1982 with the sole purpose of building VAWTs. This company, with support from NRC, has built and tested a 125-kW prototype machine (see Section 7.7) and has also developed a 150-kW commercial machine called the Adecon 19.

7.3 The Iles de la Madeleine Project

The 224-kW VAWT located on the Iles de la Madeleine in the Gulf of St. Lawrence was a joint project of the NRC and the Institute de recherche de l'Hydro-Québec (IREQ). The basic design of the turbine was specified by NRC. Detail design and fabrication were carried out by Indal Technologies Inc. of Mississauga, Ontario, under an NRC contract. There were two main objectives to this experimental project:

- to gain experience in operating and maintaining a large grid-coupled VAWT

- to obtain test data which would be used to develop analytical models of VAWT performance and structural response

A photograph of the turbine is shown in Figure 18. The turbine consists of a two-bladed rotor with equatorial diameter of 24.4 m and axial height of 36.6 m. The rotor column is carried on bearings at the top and bottom, with four guy cables holding the upper bearing in place. The blades are of extruded aluminum with a 0.61-m chord and NACA 0018 cross section. The nominal operating speed of the rotor is 36.6 rpm; however, it was operated at lower speeds during the experimental program in order to confirm various aspects of the analytical models for rotor performance and structural response. The rotor drives a 224-kW induction generator through a gearbox and a toothed belt and pulleys. The induction generator is connected to the Islands' electrical distribution network and this generator also serves as a motor to bring the rotor up to operating speed during turbine start-up.

Figure 18. 224-kW VAWT Iles de la Madeleine, Quebec.

Hydro-Québec designed and installed the foundation for the turbine and the guy anchors, as well as the electrical equipment. Hydro-Québec also carried out the installation of the turbine in the spring of 1977. Operation and data collection were managed by IREQ, which maintained personnel at the site during the evaluation period. A test program was initiated in which the turbine was operated manually at rotor speeds of 21 and 31 rpm. On July 6, 1978, the turbine rotor was destroyed in an overspeed accident; however, the resulting accident investigation found no fundamental flaws in the general concept. Therefore, a new rotor was constructed by Indal Technologies and installed by Hydro-Québec in September 1979. The turbine became operational in the spring of 1980. In the two and a half years that followed, the rotor was operated at speeds of 36.6 and 29.4 rpm in order to meet the needs of the data collection program. In December 1982 the IREQ personnel were withdrawn from the site and the turbine was operated in manual mode by Hydro-Québec staff from the Islands' central diesel generating plant. In December 1983 an automatic control system designed by IREQ was installed so that the turbine could be operated in unattended mode. However, at the time of this writing, NRC and IREQ have decided to offer the turbine for disposal.

The instrumentation installed on the turbine was quite extensive. Most notable were the strain gauges on the main shaft below the rotor and the 30 strain gauges at critical locations on the rotor. The former allowed rotor torque output measurements to be made and the latter provided important information regarding the structural dynamics of the rotor. In fact, much of the data provided confirmation of the design predictions being carried out for the 4-MW VAWT, Projet ÉOLE.

7.4 The 50-kW Projects

After installation of the Iles de la Madeleine VAWT it was concluded that for economic reasons and ease of incorporating any changes development work should be carried out with a smaller wind turbine. The size chosen was about one fifth the size of the Magdalen Island VAWT, i.e., a rotor with a swept area of about 125 m^2 and nominal rating of 50 kW.

The major objectives of these field trial projects were

- to obtain technical data on the performance and structural integrity of the units over significant periods

- to expose potential users of grid-coupled WECS to the operational characteristics of these novel generation systems, and to derive from their feedback needs and directions for further development of the technology

Two 50-kW turbines with a conventional drive train, i.e., right-angle gear box, belt, and pulleys, were installed in 1978. One was installed at Holyrood, Newfoundland, in cooperation with Newfoundland and Labrador Hydro and the other in cooperation with Saskatchewan Power Corporation at the Agriculture Canada Research Station in Swift Current, Saskatchewan.

In 1979, with the experience gained from these two machines, DAF-Indal came up with a number of design improvements, while keeping the rotor essentially unchanged.

The major design change was that the new transmission (see Figure 19) consisted of a single-mesh bull gear and pinion that connected the 80-rpm rotor to the 1200-rpm generator. Also, the bull gear and the rotor are lifted up hydraulically during operation. On initiation of a stop, the hydraulic pressure is released and the turbine and bull gear come down. The web of the bull gear comes in contact with brake pads and thus serves as a brake disk to stop the rotor. The arrangement also allows for constant guy tension, as determined by the hydraulic pressure in the rotor support system.

The bull gear, hydraulic and lubricating pumps, the motor/generator, and the complete control system for the turbine are housed in the power module and shipped after pre-assembly in the factory.

The National Research Council purchased three machines with the new design change. One of these machines was tested at the DAF plant in Toronto and then installed at Churchill, Manitoba (see Figure 20). A second machine was installed at Christopher Point, British Columbia. The third machine was installed in place of the earlier machine at Holyrood. These machines, while referred to as 50-kW turbines, have a maximum power output of about 45 kW at 80 rpm.

7.4.1 Holyrood I

The 50-kW machine installed at Holyrood was called Holyrood I. The site was selected primarily on the basis of easy access, being close to the thermal plant, and not on the basis of good winds. This machine was operated for about three years, during which time it operated for about 4500 h. It produced about 22 MWh in 3000 generating hours (see Table 10).

During the operation of this turbine considerable work was done to develop the control logic and hardware and the latching and deployment mechanism of the aerobrakes.

After observing the excellent performance of the turbines of new design that were installed at Churchill, Manitoba, and Christopher Point, British

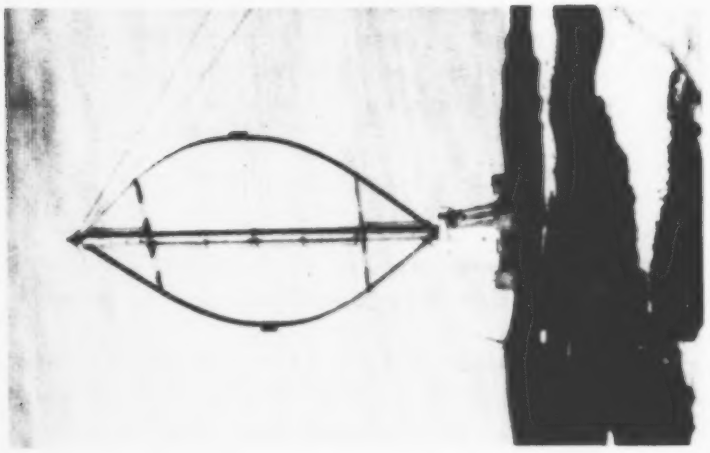

Figure 20. 50 kW VAWT installation at Churchill, Manitoba.

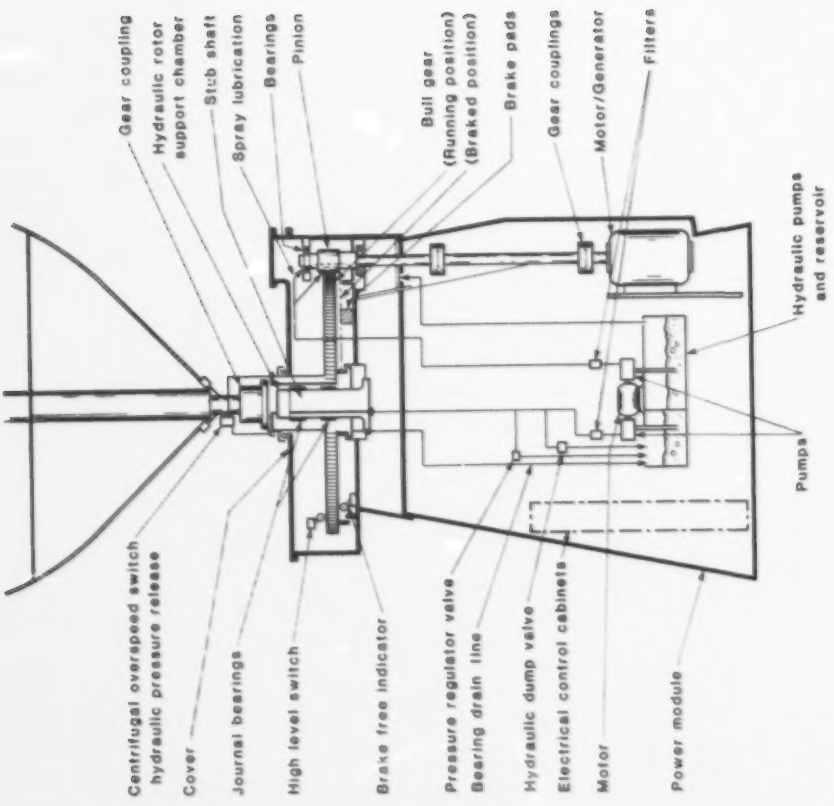

Figure 19. 50-kW VAWT power module schematic.

Table 10. 50 kW VAWT Field Trial Systems Cumulative Performance Summary (period ending December 31, 1985).

Location	Partner	Start of General Service	Operating Hours				Net Output (kWh)		Mean Wind Speed (m/s)		Current status
			Idling		Generating						
			Current Month	To Date	Current Month	To Date	Current Month	To date	Current month	To date	
Holyrood Nfld(I)	NL Hydro	June 78	Nil	1567	Nil	3015	Nil	21,600	Nil	5.67	Removed for study Nov 81
Holyrood Nfld(II)	NL Hydro	May 82	ND[1]	1991.5	ND[1]	8723.8	ND[1]	98353.0	ND[1]	5.74	Down for service
Swift Current Sask.	Sask Power	Aug 80	2.34	123.09	343.4	9996.2	3383.2	89348.6	7.7	6.52	operational
Christopher Point, BC.	BC Hydro	Mar 81	2.2	2159.5	12.1	10309.2	231.6	169259.6	4.2	5.68	operational
Churchill Man.	Churchill Research Center	Nov 81	33.6	2777.8	449.7	12415.6	10145.0	159375.0	6.2	6.47	operational
Totals			33.14	8618.89	805.2	44459.8	13759.8	537936.2			

[1] ND = No data available.

Columbia, it was decided to replace the Holyrood I machine with a machine of new design. The installation was referred to as Holyrood II. The Holyrood I machine was taken down in November 1981 and the rotor and the drive train were moved to NRC. A detailed examination of this unit revealed no serious structural damage (A-17).

7.4.2 Holyrood II

As mentioned above, the Holyrood II machine was the second generation 50-kW turbine that replaced the earlier Holyrood I machine in May 1982.

The machine produced 98.4 MWh in 8700 generating hours, i.e., about 11.3 kW per generating hour for the Holyrood I. The availability of the Holyrood II machine was much higher than Holyrood I, i.e., 76% for Holyrood II as compared to 40% for the Holyrood I. For operational histories of the Holyrood I and II see references A-35 and A-36, respectively.

7.4.3 Swift Current Installation

The Swift Current VAWT is a sister machine to the Holyrood I VAWT and was installed in 1978, the only difference being that this machine was instrumented and used for structural research and development and operated whenever data were to be recorded.

At the end of 1984 the machine was put into automatic mode as a power-producing unit. The turbine availability during 1985 was 91% and it produced about 35.9 MWh in 3600 hours of generating time. The annual average wind speed at the site for 1985 was 7.07 m/s.

7.4.4 Christopher Point and Churchill Installations

These two machines had a new type of drive train and improved control system. Prior to installation at Churchill one unit was tested at the DAF plant in 1980 and the electrical power output measured. The plot is shown in Figure 21. This power curve was used to estimate the potential energy output of all new models of 50-kW machines.

The cumulative performance summary of these two machines is shown in Table 10. Detailed operational histories and monthly performance data are discussed in reference A-37 and A-38.

The overall availability of the Christopher Point machine for the period 1981 to 1983 was 75% and it produced 169 MWh for a generating time of 10 300 h, i.e., 16.4 kW per generating hour. The average wind speed at the

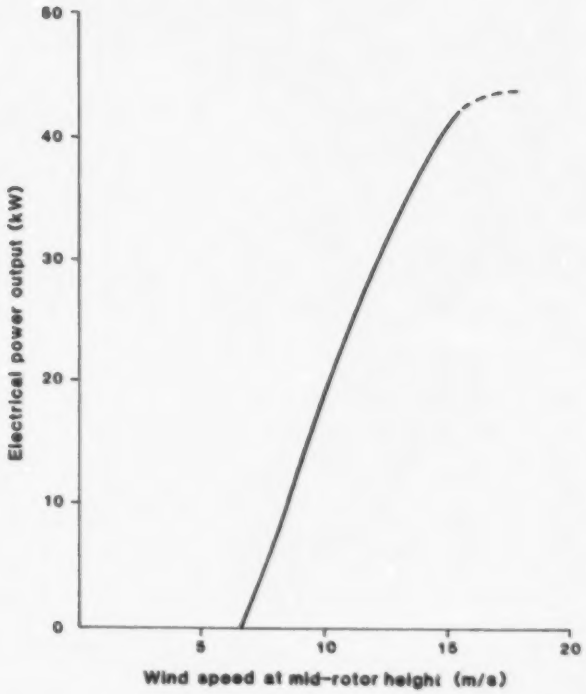

Figure 21. 50-kW VAWT power curve, Churchill, Manitoba.

site for this period was 5.68 m/s. The corresponding data for Churchill VAWT for 1982 to 1985 is

Availability	= 72%
Production	= 158.487 MWh
Generating hours	= 12 047
Production/Gen. hour	= 13.2 kW/h
Average wind speed for period	= 6.42 m/s

While the average availability for the total period for the two turbine is 72 to 75% there were many months when the availability was consistently approaching 99%. For example, in 1985 at Christopher Point three months were lost due to a short in a generator. For the rest of the nine months in 1985 the availability was 99.75%.

7.5 Wind/Diesel Systems

7.5.1 Introduction

There are over 800 diesel generator sets with an aggregate rating of over 500 MW providing electricity to more than 300 Canadian communities that are

not connected to major power grids. Ratings for individual sets range from 20-50 kW to over 1 MW rating. A typical single-community powerhouse has three or four sets of different ratings to ensure availability of power and to achieve reasonable load fractions over wide ranges of demand level.

In addition to community supplies, there are hundreds of small autonomous power systems in the remote regions of Canada, powering individual dwellings, nursing stations, communications relay stations, navigational aids, automatic weather stations, and similar demands. These loads typically average a few hundred watts to a few kilowatts; the smaller ones often incorporate battery storage.

Beyond these domestic applications, there is a vast market for autonomous electric powerplants in developing countries. Modest initial needs for communications and part-time lighting will quickly escalate to include moderate demands for full-time power for cooking, pumping, and other mechanical drives.

Where the wind regime is appropriate, wind energy can cost-effectively augment diesel-electric generation. In small systems incorporating energy storage, the wind energy can be used to charge batteries. In larger systems wind energy can be used directly to provide for part of the load, leaving the diesel set to provide for the remainder and to accomplish load-following. The additional cost of adding the wind energy components to the system must be amortized by the saving of diesel fuel. The delivered cost of diesel fuel varies greatly among remote communities, depending primarily on the distance and difficulty of transportation. Effects on the type and frequency of maintenance of both diesel and wind energy components must also be accounted for.

Incorporating wind energy into traditional community-scale diesel powerplants involves several technical challenges, most of which are related to control system design and overall system engineering. Both load and wind energy vary randomly with time, thus diesel controls may have to maintain stability for the entire system. Means must be provided to absorb surplus power when wind power exceeds instantaneous load less the minimum permissible load on the diesels. Automatic dispatching of sets within a powerhouse must be carefully prescribed to avoid multiple starts, prolonged running at low loads, and momentary overloads, while maintaining reliable, high-quality supply to the community. Current technology addressing these and other challenges is evolving rapidly in many nations, thereby permitting a greater fraction of wind energy in a given autonomous system.

Canadian activities in this field have progressed from preliminary studies and laboratory-scale experiments, to field-scale research and development

projects and early demonstration systems. The following two sections outline these activities and summarize the current status of various parts of the technology.

7.5.2 Toronto Island 12 kW Project

The development of wind-turbine-assisted diesel generators in Canada began in 1978 with the installation at Toronto Island in Ontario. This small-scale demonstration project consisted of a 10-kW vertical axis wind turbine coupled to two 3.7-kW single-phase induction motors and a 13.4-kW diesel engine coupled to a 12-kW single-phase, 60-Hz alternator. Electrical resistors were used to simulate the variable load. Provision was made to operate the wind turbine either electrically coupled or mechanically coupled to the diesel generator.

The results (E-38) showed that substantial fuel savings were possible with wind assisting the diesel generating system in regions where annual average wind speed was higher than about 5.5 m/s. However, due to the small scale of the experiment, it was found that some components had low efficiency (e.g., single-phase generators were only 70% efficient) thus degrading the fuel savings. The recommendation from this project were that

- a larger, community size, wind/diesel experiment should be carried out
- the turbine starting loads should be reduced so as not to load the diesels excessively
- the excess wind energy should be utilized rather than wasted

7.5.3 The Sudbury Projects

General - As recommended from the Toronto Island wind/diesel project it was decided to construct and install a 100-kW wind/diesel system on a hilltop at Coniston, Ontario (near Sudbury). This plant was commissioned in January 1982 and named Sudbury Wind/Diesel Test Site. The project was sponsored by NRC, Ontario Ministry of Energy (OME), Energy Mines and Resources Canada (EMR), Dominion Aluminum Fabricating Ltd. (DAF) (now called Indal Technology Inc.), and Ontario Hydro, who also managed the job for all sponsors. This site was selected because it had a good wind regime and an extremely cold northern climate, and yet it was easily accessible from Toronto and Ottawa. The powerplant, see Figure 22, comprised two 50-kW diesel generators, a 35-kW vertical axis wind turbine, a dump load, and a simulated remote community load. The turbine was mechanically connected to one of the two diesels by means of an over-running clutch. The other diesel generator operated independently as required.

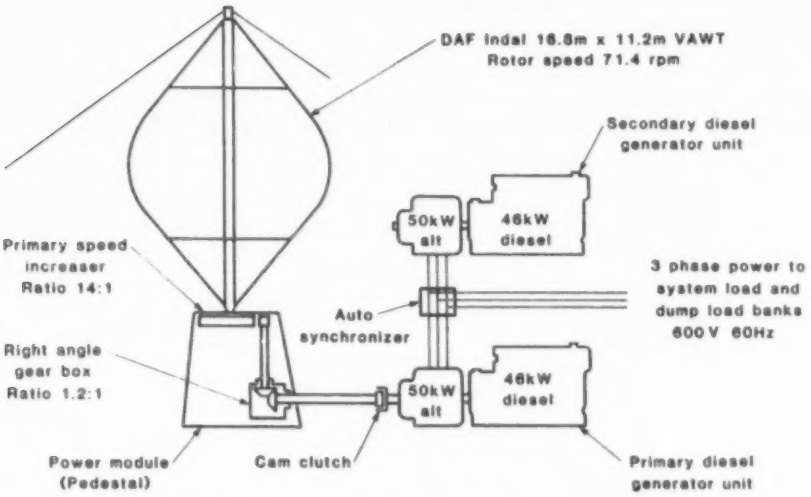
DAF Indal 16.8m x 11.2m VAWT
Rotor speed 71.4 rpm
Secondary diesel generator unit
50kW alt
46kW diesel
Primary speed increaser Ratio 14:1
3 phase power to system load and dump load banks 600 V 60Hz
Auto synchronizer
Right angle gear box Ratio 1.2:1
50kW alt
46kW diesel
Power module (Pedestal)
Cam clutch
Primary diesel generator unit

Figure 22. 100-kW wind turbine assisted diesel generator system, Sudbury Ontario.

Sudbury I - The objectives of the Sudbury I project were

- to demonstrate that a VAWT can be effectively and reliably coupled mechanically to a diesel-electric generating plant of approximately the same power rating

- to demonstrate that a wind-assisted diesel-electric generator system can operate automatically and reliably in the environment of the Canadian north

- to gather test data to verify design assumptions, evaluate system economics, fuel savings, etc., and to make recommendations for further development

The system was operated for about 6 months with ambient temperature varying between -35 and +31°C. An actual scaled-down community load pattern from Attawapiskat, Ontario, was used as the independently changing community load for the wind/diesel system.

The test results showed that

- coupling the wind turbine mechanically to the diesel generator is technically sound

- the system voltage and frequency fluctuations were within acceptable limits set by Ontario Hydro for small generating systems

- the measured fuel savings, due to wind, confirmed theoretical predictions, and amounted to over 40% in high winds

Sudbury II - The Sudbury I project successfully demonstrated feasibility of mechanical coupling of wind/diesel systems. However, in some cases the siting requirements of wind turbines and/or diesels may not permit mechanical coupling. Therefore, it was decided to study the electrical coupling of wind/diesel generators and also to explore operation of the wind turbine in a "stand-alone" mode (i.e., whenever the wind power exceeds the load the diesels are shut down and the wind turbine alone supplies the demand load). The same components used in the Sudbury I project were rearranged to the electrically coupled/stand-alone configuration.

The results of the test program called Sudbury II are

- start-up and synchronization of a wind-turbine-driven alternator to a 60-Hz diesel generator system were automatically performed over a wide range of wind speeds

- utility requirements for frequency and voltage regulation were met by the wind/diesel system in an electrically coupled mode

- the electrically coupled wind/diesel system is not as effective in fuel saving as the mechanically coupled mode

- the feasibility of the stand-alone concept was proven; however, the voltage excursions exceeded utility guidelines by a narrow margin, and considerable energy was lost to the dump load

After completion of the above-mentioned two phases of the wind/diesel program at the Sudbury site, the wind/diesel installation was moved to the Atlantic Wind Test Site. At AWTS it will be used as a test bed for future wind/diesel Research and Development.

7.5.4 Wind/Diesel Computer Simulations

Mechron Study - Mechron Energy Ltd. of Ottawa has developed a 15 to 150-kW ac diesel-electric power system, called Cycle Charge 4000, for small remote community applications. The load is primarily supplied from large capacity batteries and the diesels are operated mainly to charge the batteries. Mechron, under contract to NRC, has carried out a study to determine the feasibility and economics of a wind-assisted Cycle Charge system. Twelve different configurations involving different battery and WECS ratings were simulated and economic viability was examined using fuel prices of 30¢, 90¢ and $1.50 per litre (A-46).

The Cyclic Charge system with fuel prices at 90¢ and $1.50 per litre shows significant savings (15 to 30%) over conventional diesel generators and combination of wind turbines with Cycle Charge shows even greater savings (26 to 46%). At 30¢/L the Cycle Charge is marginally better than the traditional diesel system; however, addition of wind power makes it slightly more expensive than diesel alone.

GasTOPS Programs - GasTOPS Ltd. of Ottawa was awarded a contract to develop two programs: one to model the long-term system performance and economics of wind/diesel systems and the other a dynamic model to check the control and stability of the proposed wind/diesel systems.

In the first, system configuration is specified from a repertoire of components (HAWT, VAWT, DG, storage, load, etc.). Long-term fuel savings can be predicted by the quasi-steady-state model and the results analyzed with the Lotus 1-2-3 economic spreadsheet. The fuel saving model operates with flexible time format (non-uniform time increments) for the wind and load input data which permits reducing the data file size during periods when these parameters are fairly steady or are at a low level. Normally AES hourly wind data would be used. The program is written in FORTRAN and currently is set up to run on a Digital Equipment VAX computer. It could be adapted to smaller computers such as an IBM PC. Some familiarity with FORTRAN programming is required in order to make changes to the system configuration or control strategy. The intention is to build up a library of the most common configurations.

In the second, a fully dynamic model is used for detailed simulation of transients due to wind gusts and load changes, as well as for optimization of the control system. This operates on the NRC Hybrid Computer Facility. Its use is fairly complex and would normally be contracted to a company such as GasTOPS. The program operates at approximately one-tenth of real speed and analogue display is available in the form of strip chart recordings in addition to the summary printouts. Transients down to the one-second time frame can be analyzed.

7. The Indal Technologies Inc. 500-kW VAWT at the Atlantic Wind Test Site

Following the development of the 50-kW VAWT with its unique drive train, Indal Technologies Inc. of Mississauga, Ontario, continued with the design of a 500-kW unit which has rotor dimensions very similar to those of the Magdalen Islands VAWT. Some of the design work for this turbine relied on the early analytical methods developed and verified with the Magdalen Islands experimental VAWT and on operational experience gained in the testing of the 50-kW VAWT Field Trial VAWTs.

In mid-1983, NRC purchased the second prototype 500-kW, Series 6400 VAWT from Indal Technolgies and the turbine was installed at the Atlantic Wind Test Site in Prince Edward Island in September to December 1983. The Atlantic Wind Test Site was contracted by NRC to prepare the foundations and erect the turbine. The commissioning of the turbine was carried out by Indal, in early 1984. Under the direction and sponsorship of NRC, AWTS was contracted to monitor and maintain the turbine, as well as the instrumentation and data acquisition systems. Indal provided warranty support during the commissioning and acceptance testing of the turbine. The National Research Council has given the name "Project Aquilo" to the testing and evaluation of the turbine.

The turbine at the AWTS is shown in Figure 23. The two-bladed rotor has an equatorial diameter of 24.4 m and an axial height of 36.6 m giving a swept area of 595 m^2 (6400 ft^2). The blades are of extruded aluminum with a chord of 0.737 m and NACA 0015 cross section. The support system consists of three pairs of guy wires, independently terminated at the ground anchor point and the rotor upper bearing. The transmission of the turbine uses a

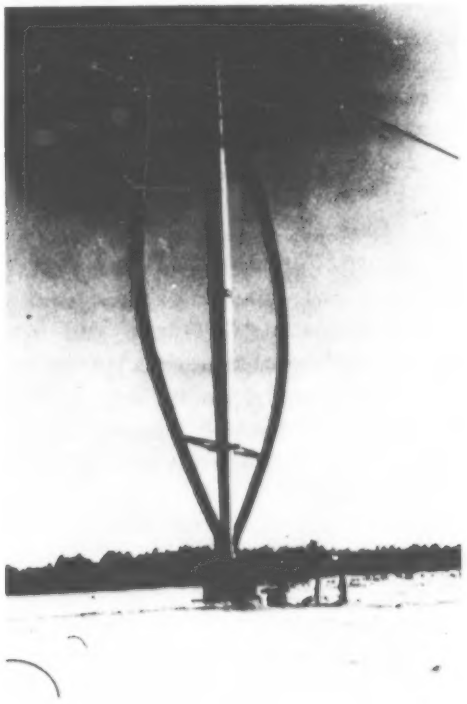

Figure 23. 500-kW Aquilo VAWT at the Atlantic Wind Test Site.

single 2.55-m diameter bull gear which is directly coupled to the bottom of the rotor. Nominal rotor speed is 45 rpm. Two 261-kW induction generators are mounted on diametrically opposite sides of the bull gear with their shafts in a vertical orientation. Each generator is driven by its own pinion gear which meshes with the bull gear. The generators feed power into the Prince Edward Island electrical distribution network.

The drive train of the turbine is innovative because the bull gear also serves as the "disk" of the brake. The bull gear is lifted by hydraulic pressure off a set of brake pads during turbine operation. To stop the turbine, the hydraulic pressure is released and the rotor weight forces the bull gear onto the brake pads. This design allows fail-safe braking to be easily incorporated into the control system. Automatic guy tensioning is also provided by applying this same hydraulic pressure to the upper bearing of the rotor which lifts the bearing and tensions all six guy cables to the same load.

The turbine was fully instrumented with 40 strain gauges at critical locations on the rotor and electrical power output transducers on the generators. A Hewlett-Packard HP-1000 A-700 computer was installed at the AWTS by NRC for the sole purpose of acquiring all of the test data from the turbine. Software developed by Sandia National Laboratories of Albuqueque, New Mexico, was extensively modified by DMR Group Inc. under contract to NRC. The computer and software were given the name High Speed Data Acquisition System (HSDAS). The system was designed to carry out a number of data analysis routines which are unique to wind turbine field testing. It represented a significant investment on the part of NRC and it has proven itself to be a powerful tool for the evaluation of wind turbine field test data.

During 1984, the turbine experienced a number of problems which were typical of prototype development. However, during most of 1985, the turbine was more reliable and as a result, by the last quarter of the year, the turbine was operating in unattended automatic mode, with only minor control system shutdowns which were manually reset by AWTS staff. However, on November 15, 1985, the turbine experienced a blade failure at the connection to the upper horizontal strut while operating in automatic mode. Fortunately, the control system brought the turbine to a safe stop, preventing any further damage to the turbine. Metallurgical investigations of the failed blade by NRC found that a fatigue failure had been initiated at a bolt hole in the blade. At the time of this writing, Indal is preparing to install a new redesigned rotor and begin recommissioning the turbine in the first quarter of 1987. Financial assistance has been provided by the Department of Energy, Mines and Resources for the rotor redesign and testing.

In spite of these difficulties, Project Aquilo has been an extremely valuable exercise. The turbine provided reliable data from which analytical methods for rotor structural dynamics were verified. Indal has developed a state-of-the-art expertise in these analytical methods and has used this expertise in the rotor redesign. Furthermore, the original turbine accumulated 3120 h of operation and generated 320 MWh of energy, most of this occurring in 1985. Indal is presently studying other versions of the turbine in an effort to make the unit cost competitive for use in "wind farm" applications.

7.7 The Low cost 125-kW VAWT

As mentioned in Section 7.2, Adecon Energy Systems Incorporated of Toronto decided to develop a low-cost machine. The approach they took was to use a very light blade, external frame support structure and a lower power loading. The blade was made with four small extrusions joined rather than a much heavier single extrusion. The external frame structure allowed a lighter central column, lighter bearings, reduced the size of foundations, and raised the mid-rotor height for better energy yield. The lighter structure allows the use of a crane with smaller lifting capacity. The lower power loading allowed a lower cut-in wind speed and higher yield.

The prototype machine (see Figure 24) has a rated power of 125 kW with a 17 m wide and 25.5 m high rotor, i.e., 283 m^2 swept area. The external lattice framework supports the power module 17 m above the ground. The machine was installed at Atlantic Wind Test Site, Prince Edward Island, in February 1985 and has completed preliminary testing.

Adecon is building a commercial model "Adecon 19" with a 150 kW rating to be tested near Toronto, Ontario. This design has incorporated hinged blades for filtering the inherent cyclic aerodynamic torque loads and eliminating the butterfly mode of vibration by lowering the resonant frequency below any operating frequency.

7.8 Delta-blade Wind Pumps

7.8.1 Introduction

The delta-blade wind turbine concept was originated by Kentfield and Narrie of the University of Calgary. This concept was subsequently developed by Kentfield and its theoretical performance confirmed by testing a 3.3-m diameter model in the NAE 9 m × 9 m wind tunnel in 1979. Abax Energy Services began investigating the application of delta-blade wind turbine in 1978 for pumping large quantities of water.

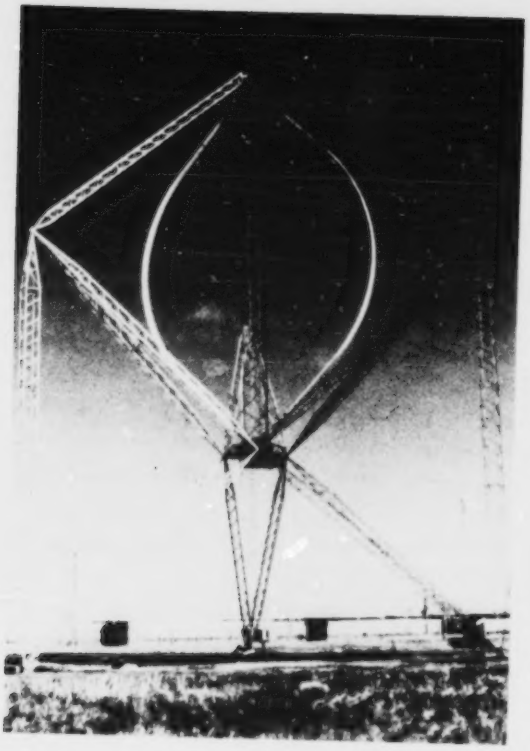

Figure 24. The Adecon 125-kW VAWT at the Atlantic Wind Test Site.

The delta-blade turbine uses sharp-edged flat-plated delta-wing-like surfaces for blades. The flat-plate blades are simple to make and the delta-shaped blades stall at higher angles. As well, an automatic stroke-controller mechanism was introduced to maintain the turbine near its optimum efficiency.

7.8.2 WP20 and WP-50 Wind Pumper Tests

WP-50 Turbine - Abax Energy Services, with funding from the Alberta/Canada Energy Resource Research Fund (A/CERF), designed a horizontal axis 16.0-m diameter prototype turbine in February 1983. The eight-bladed rotor (see Figure 25) drives, via a direct mechanical linkage, twin double-acting variable stroke piston pumps. Automatic high wind speed protection is accomplished by the rotor axis being offset from the yaw (tower) axis.

The turbine was fabricated and erected at the Abax plant and preliminary operations were completed in October 1983. The evaluation of the turbine performance was funded by NRC and carried out in late 1985. The turbine

Figure 25. WP-50 wind driven water pump at ABAX, Calgary, Alberta.

can pump 91 000 L/min (at 9.1-m lift) at a wind speed of 13.3 m/s. A report will be issued.

WP-20 Turbine - The WP-20 is an eight-bladed, 5-m diameter turbine with a similar configuration to the WP-50. This machine was manufactured by Deltx, a subsidiary of Abax Energy Services of Calgary.

This unit was tested at the Lethbridge Wind Test site, Alberta, in the winter of 1985/86. During the test, the pump stroke was set at a fixed value of 7.6 cm. The WP-20 reached a maximum pumping rate of 21 L/s in a wind speed of 8.5 m/s (at 6.1-m lift). The test report is in preparation.

7.9 Megawatt-scale VAWT

7.9.1 Preliminary Studies

In the mid-1970's the consideration of wind energy conversion systems for regional and national power supplies led to investigations of the effects

of wind energy conversion system unit size on cost-effectiveness. Preliminary calculations at NRC's Low Speed Aerodynamics Laboratory suggested improved cost-effectiveness with increased unit size up to at least megawatt-scale machines.

Shawinigan Engineering Company Limited won a contract to conduct parametric studies of VAWTs ranging from 1000 to 8000 m^2 swept area. A total of 72 cases were examined incorporating selected values of:

Swept area	A = 1000 to 8000 m^2
Rotor height/diameter ratio	$H/2R$ = 1 to 2
Solidity	C/R = 0.05 to 0.10
Number of blades	N = one to 3
Turbine center/height ratio	h_c/H = 0.5 to 1.0
Rated power/wind power ratio	Kp_{max} = 0.5 to 2.0

A single wind regime typical of exposed sites on Canada's east coast was specified as follows:

V = 8.0 m/s at 30 m height
k = 2.0 (i.e., Rayleigh distribution)
α = 0.16 (the wind shear coefficient)
ρ = 1.2256 kg/m^3

In each case preliminary design work was carried to the stage required for reasonably accurate cost estimates. Canadair Limited was responsible for aerodynamic and structural design and for cost estimating the rotor. Shawinigan compiled overall system cost estimates and computed relative costs of energy based on 30-year design life and an assumed production of 20 units per year for 10 years. Major conclusions from this study were (E-13)

- Large capacity, up to 10 MW, Vertical Axis Wind Turbine Generator (VAWTG) plants for the production of electrical energy are technically feasible in that no fundamental obstacles to their development have been uncovered.

- The costs per unit power of large VAWTG plants decrease with increasing installed power, at least within the study limits of 600 kW to 10 MW.

- Because the cost studies have been conservatively carried out and because the engineering studies have shown that future improvement of the design is possible, the costs of actual production units are expected to be less than those found in this study.

- The installed cost per unit of annual average power output for the first 14 least-cost VAWTG units are found to vary between $2600 and $3300/kW (corresponding to 32 mills/kWh and 40 mills/kWh).

Several years later, as part of a major *Technology Development Study of Vertical Axis Aerogenerator Systems Yielding the Lowest Cost of Energy* (E-17 to E-31) DAF Indal prepared cost analyses for a range of smaller VAWTs from 600 to 2400 m^2. There was reasonably good agreement between the SECL and DAF cost projections, and certainly strong evidence of improved cost effectiveness as unit size increased to more than 1 or 2 MW.

Similar results were found in other countries (e.g., United States, United Kingdom, Sweden) which were concentrating on the more conventional HAWT configuration.

7.9.2 Prototype Project Definition

The SECL parametric study recommended that a preproduction VAWTG be designed and installed in an electrical grid system to demonstrate the technical and economic viability of a large-capacity VAWTG unit for the production of electrical power. The power and energy costs for the production version of the recommended 4000 m^2 two-bladed prototype were forcast to be $723/kW installed, $3278/kW average, 39.7 mills/kWh for a unit of 3878-kW maximum power rating. The unit would supply the grid system with an average of 7 489 800 kWh/a in the wind regime specified for the study.

To establish the expected cost and schedule to design, build, and evaluate such a prototype, Shawinigan undertook a more detailed examination of the recommended case (E-14) and prepared a Project Definition (E-15) in July 1979 which was subsequently updated (E-16) in June 1980.

It was evident that electric utility agencies would be the predominant users of megawatt-scale WECS and hence all preliminary studies were conducted with the participation of IREQ, NRC's partner in the experimental VAWT project on Iles de la Madeleine (recall Section 7.3). Before embarking on the megawatt prototype VAWT, IREQ and NRC jointly sponsored a comparative study of large-scale VAWT and HAWT technologies. The *Study of Large Wind Turbine Generating for Electrical Power Generation* comprised:

PHASE I: Review of the state-of-the-art of existing and projected wind machines

PHASE II: Detailed technical comparison of the HAWT and the VAWT configurations

PHASE III: Comparison of cost and economic aspects of HAWTs and VAWTs

The major objective of the study was to make an equitable comparison between HAWTs and VAWTs on technical, cost and economic aspects, on the basis of normalized performance and cost data generated for all components for both types of machines.

The three comprehensive Phase reports contain proprietary data on performance and cost of then-current megawatt HAWTs and submegawatt VAWTs. These data were used to compare with estimated costs of megawatt-scale VAWTs of similar swept area and/or energy yield. The principal conclusions as published in the *Executive Summary* of all Phases of the study (E-32) were:

- The single most important application of wind energy conversion systems which will yield maximum national impact, by serving all sectors of the economy, is in the electrical utilities. This is because the economics of manufacturing and operating large machines is more favourable than that of small machines.

- From the viewpoint of the present state-of-the-art, HAWTs are more advanced in design and operating experience than VAWT units. Both concepts show promise of technical and economic viability. The environmental issues are similar for both HAWT and VAWT installations.

- In comparing the COE for the HAWTs and VAWTs in the Phase III study, the lowest COE of 2.69 ¢/kWh is given by the 8-MW VAWTG-AC at a site having an annual mean wind speed of 8.72 m/s (19.5 mph) and 4.93 ¢/kWh for the 5-MW VAWTG-AC at a 6.26 m/s (14 mph) site. The computations of COE use costs in June 30, 1980, Canadian dollars, a fixed charge rate of 0.18 and an operation and maintenance levelizing factor of 2.

- Increased activities in research and development and design optimization of WECS will effect a reduction in capital costs and improve breakeven costs. Review of ideas for future advances in the design of the HAWT and the VAWT indicate that the VAWT will remain competitive with the HAWT. For the VAWT a power train is feasible in which the generator is directly coupled to the rotor thereby eliminating the mechanical speed increaser. Such a power train, together with improvements in rotor performance, would reduce the cost of energy due to the associated increase in energy production, reduction in capital cost and simplification of the power train.

- The VAWT is fully competitive with the HAWT within the accuracy of the analysis. In fact, the specific data indicate technical and economical superiority for the VAWT.

The report again recommended that a prototype multimegawatt VAWT should be designed, manufactured, and installed to supply power into a utility network to demonstrate the technical and economic viability of large VAWTs.

7.9.3 Projet ÉOLE

In March 1981 NRC and IREQ signed a Preliminary Work Agreement to lay down the major specifications for a 4000-m^2 VAWT prototype based on the studies described above and on the extensive experience existing in both agencies as a result of previous individual and joint VAWT research projects such as Iles de la Madeleine. A small group including NRC, IREQ, Hydro-Québec, Shawinigan Engineering Company Limited, and Canadair prepared the *Preliminary Technical Definition of Project Aeolus* (later Projet ÉOLE, named after the Roman God of the Winds) (A-53). This document

- listed major design parameters (see Figure 26)

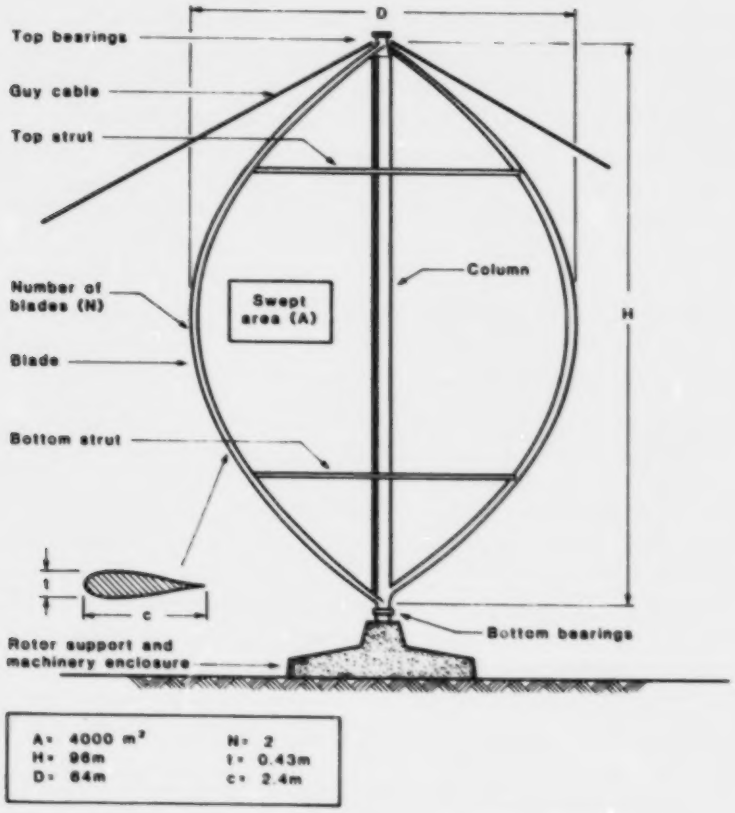

Figure 26. Projet ÉOLE components and dimensions.

- specified values for certain design parameters
- defined terms of reference for studies required to establish values of the other design parameters
- suggested subsystems and interface specifications needed to assure subsystem compatibility
- provided guidance on design considerations such as reliability, safety, environmental interactions, instrumentations, etc.

On March 17, 1982, Hydro-Québec/IREQ and NRC signed an Agreement to share equally the estimated $35.2 M cost of designing, constructing, and evaluating the 4000 m^2 prototype VAWT. Hydro-Québec was tasked with managing Projet ÉOLE on behalf of both NRC and IREQ as shown in Figure 27. Overall design responsibility was contracted by Hydro-Québec to Experts Conseils Shawinigan Inc. (ESCI) who prepared working drawings and specifications for tendered fabrication contracts let by Hydro-Québec. Major suppliers were

Versatile Vickers - Rotor
Canadian General Electric - Generator and Controls
Hayes Dana Corporation - Drivetrain and Brakes

Among several potential sites considered, four were instrumented, and the one near Cap Chat, Quebec, was selected (recall Section 3.5.3) (see Figure 28). A Preliminary Design Review was held in December 1982 and Critical

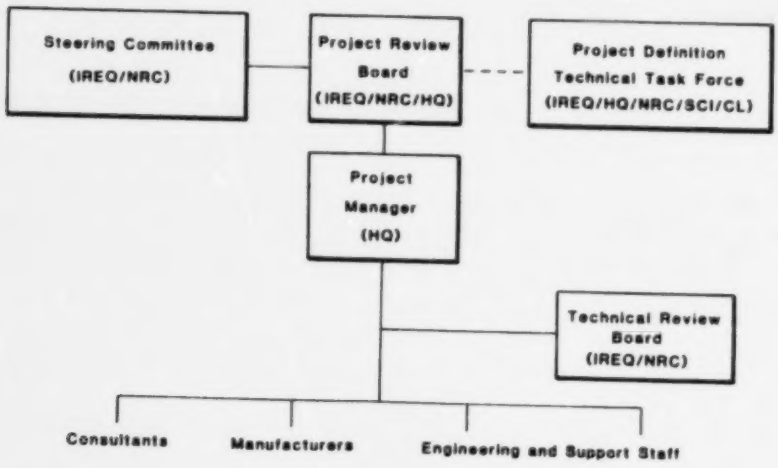

Figure 27. Projet ÉOLE organization.

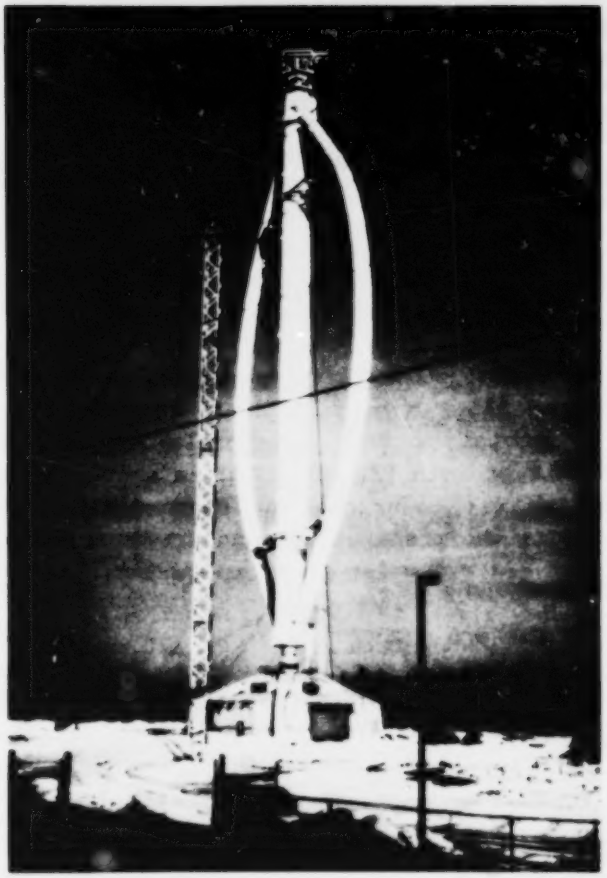

Figure 28. 4MW ÉOLE VAWT, Cap Chat, Québec.

Design Review (involving experts from other countries) was held in September 1984. The original schedule called for erection during the autumn of 1985 with commissioning and evaluation in 1986 and 1987. Site work and the powerhouse building are complete, the generator and controls were delivered and installed to schedule but slippage of rotor fabrication postponed erection until late summer 1986. Commissioning and preliminary evaluation were rescheduled for 1987/1988. Latest estimates suggest the project costs could exceed the original budget by about 10%.

Two significant changes have occurred in the milieu for megawatt-scale wind turbines since the initiation of Projet ÉOLE. Firstly, other megawatt-scale prototypes in the United States, United Kingdom, Sweden, and Germany have proven to be considerably more expensive and more time-consuming to develop than anticipated. On the other hand, intermediate-scale systems are reaching technical maturity faster and are filling the most attractive

commercial opportunities. Though non-oil-producing European countries continue to support wind energy R&D, their perceived optimum unit size has diminished to about 1 MW.

Secondly, the expected continued increase of oil prices from $30/bbl towards and beyond $50/bbl has not materialized - indeed a reversal of oil prices to less than $15/bbl has occurred. This has substantially reduced the perceived urgency for research and development of alternate energy sources. Indicators of this waning urgency include discontinuation of alternative energy system tax credits in the United States, and dissolution of the NRC Division of Energy. In light of the general conditions outlined above, and in view of general restraints, Hydro Québec/IREQ and NRC had to consider terminating Projet ÉOLE in the spring of 1986, although such a move would have significantly restricted the technical benefits.

In April 1986, Lavalin Inc. proposed arrangements by which ECSI would take over the project, complete construction and commissioning, and operate the machine as a revenue-producing powerplant while gathering longer term performance and operational data. After negotiations, NRC, Hydro-Québec, and IREQ agreed to the transfer of Projet ÉOLE to ECSI as of May 1, 1986. ECSI anticipate the machine will be erected by December 1986 and commissioning and preliminary evaluation will be achieved by spring 1987; thereafter operating and maintenance information will be gathered during continued revenue operation under a power purchase contract between ECSI and Hydro-Québec.

8.0 OTHER CANADIAN WIND ENERGY PROJECTS

8.1 National Conservation and Alternative Energy Initiative

In May of 1985 a decision was announced which gave to the Department of Energy, Mines and Resources (EMR) the mandate for continuing the support of renewable energy. In the announcement a new initiative called the National Conservation and Alternative Energy Initiative (NCAEI) was established with a funding level of $300 million over the next three years. It eliminated direct grants to energy users and concentrated more on support programs for energy research and demonstration, technology transfer, and improving consumer awareness as a means to encourage investment in energy efficiency.

The alternative energy components of NCAEI are to support the RD&D needed to address the technical problems and improve the competitiveness of these technologies. The financial support is meant to overcome such barriers as market price distortions, lack of information to investors, high perceived risks to users, and small under-capitalized industries.

The NCAEI is also accompanied by an effort to increase federal/provincial collaboration in the energy sector. Specific agreements have been or are under negotiation with the provinces. Under NCAEI, specific programs of interest to the wind energy community were developed; the Wind Energy R&D Program, the Special Project Demonstration Program, and the Remote Community Demonstration Program.

8.1.1 Wind Energy R&D Program

The Wind Energy R&D Program is managed by the Renewable Energy Branch of EMR. The ultimate goal of this new federal program is to encourage research to establish a technology base and to support industry in confirming the viability of wind energy as an energy supply alternative.

As a consequence of the limitations on manpower and research expertise within REB/EMR, the management structure uses external expertise in specific technologies by employing R&D Technical Advisory Committees (TACs). The intent, when inviting experts to serve on the TAC, is to obtain a broad representation from manufacturers of WECS, potential users of the technology, key individuals from research centers and testing facilities, and individuals where expertise complements that already represented in the other committee members. The primary function of the TAC is to provide advice regarding R&D priorities and to assist EMR in directing the R&D Program.

Six priority areas have been identified for R&D in Wind Energy. These priority areas are largely tied to the development of cost-effective and

reliable wind turbines that will be needed to respond to the near- and long-term Canadian market development, these priorities are

- Generic Research
- Technology Development
- Wind/Diesel System Development
- Technology Testing and Monitoring
- Wind Farms/Arrays
- Technology Transfer

A budget of approximately $1M per year is devoted to this R&D program.

8.1.2 Special Project Demonstration

The objective of this demonstration effort is to accelerate the adoption and commercial use of renewable energies as well as to increase the awareness of the Canadian public and of the commerical sector to the opportunities for their utilization. The Special Project Demonstrations program is meant to be a link between research and development activities and product commercialization. Technology transfer is an important part of these demonstrations, as these types of projects produce valuable information in support of the renewable energy industry in terms of improved systems and cost performance. One project approved was the installation of a 15-m diameter water pumping windmill to produce marshland. This project is managed by Ducks Unlimited and the water pumping turbine is manufactured by DELTX Windpump Corporation.

8.1.3 Remote Community Demonstration Program

The Remote Community Demonstration Program (RCDP) was introduced in 1980 and designed to encourage communities not connected to the main electrical grid or natural gas supply system to investigate their off-oil opportunities and then to fund selected demonstration projects. Under Phase I, nine prefeasibility studies related to wind energy have been completed. Table 11 provides a list of these studies and their corresponding funding levels. Phase II, which is the demonstration stage of the program, is now underway. Two concept proposals have been approved up to now and two projects are underway.

Concept Proposals - St. Anthony, Newfoundland: Wind monitoring for a multi-unit installation is underway and the proposal for the demonstration portion is being developed; Cambridge Bay, North West Territories: It is proposed to interconnect to the local diesel grid a wind turbine with an output capacity between 60 and 150 kW.

Table 11. Remote Community Demonstration Program (RCDP) PHASE I

Province	Location	Description	RCDP Funding ($000)	Total ($000)
Northwest Territories		Wind/Hydro Hybrid	60	60
British Columbia	Kitkatla	Wind Feasibility	22	27.5
Quebec	Iles de la Madeleine	Windfarm (Wind Measurement)	36	48
		Small Windmills	50.4	50.4
Ontario	Mud River	Wind Feasibility	3	3
Newfoundland	South Coast	Wind Feasibility	53	53
	Labrador Coast	Wind Feasibility	14	14
	St. Anthony	Wind Feasibility	21	25.3
	Pinsents Arm/ Norman Bay	PV/Wind Cycle Charge	30.6	30.6

Projects Underway - Fort-Severn, Ontario: The Fort-Severn wind/diesel demonstration system consists of a 60-kW HAWT built by Howden Group of Canada connected to three diesel generators, 85, 125, and 175 kW. The erection of the wind turbine is scheduled for September 1986. The project is managed by Ontario Hydro and contributions are provided by Energy, Mines and Resources Canada, the Ontario Ministry of Energy, Howden group of Canada, and Ontario Hydro; Kuujjak (Fort Chimo), Quebec: Hydro-Québec has undertaken a project to install a 65-kW Bonus wind turbine connected to the diesel grid of the community. The project is managed by Hydro-Québec and contributions are provided by Energy, Mines and Resources Canada and Hydro-Québec.

8.2 University Activities

Several universities are also conducting research in wind energy. The two main sources of financing for universities are NSERC which has already been described on the Research Agreement Program (RAP) from EMR. This program provides grants for research and development projects in natural, physical, and social sciences and engineering to educational institutions. The program promotes exchange of information, expertise, and technology between participating organizations and government. Each year several projects are approved. Some universities have identified groups working in wind energy research; the following are the most important: Laval University, Quebec; Sherbrooke University, Quebec; Ecole Polytechnique de Montréal, Quebec; University of Waterloo, Ontario; University of Calgary, Alberta; and College of Trade and Technology, Newfoundland. Other universities have individuals involved in wind energy research activities.

The Natural Sciences and Engineering Research Council (NSERC) also provides grants to university researchers in many areas, including wind energy. However, no projects are underway at present.

8.3 Other Projects of Importance

8.3.1 Hall Beach Project

Health and Welfare Canada operates nursing stations, clinics, hospitals, health centers, and stations in remote locations of Canada, especially the North. The Northwest Territories have 68 locations, the Yukon 211, and a further 60 are located above the 55th parallel in the provinces of British Columbia, Alberta, Manitoba, Saskatchewan, Ontario, and Quebec. Hall Beach is one of the 30 nursing stations in the North West Territories with a utilization capacity of 15 kW. The load is supplied either by the station's own diesel generator or by the Northern Canada Power Commission. Energy costs range from 30 to 70¢/kWh as compared to the national average of 5¢/kWh. Because of the high costs for electrical power, together with problems encountered with respect to heating oil transportation and storage and its effect on the environment, Health and Welfare Canada decided to investigate the potential for using wind energy. A wind data assessment program was carried out and Hall Beach was selected for the demonstration of a 10- to 15-kW wind turbine.

A NorthWind Power Co. wind turbine was selected for the demonstration. The machine (rated at 9 kW) was sent to AWTS to test the performance, operational, and reliability aspects for suitability in northern climates. Because of problems encountered and retrofits that were required on the unit, Health and Welfare Canada decided that the machine should undergo an additional testing period at the AWTS during the winter of 1985/86. In April 1986 the unit fell while being lowered for mechanical adjustments and there was considerable damage to all its components. Despite the accident Health and Welfare Canada is now planning to investigate the possibility of using a new wind turbine (12 to 15 kW output) and proceeding with the demonstration. If this demonstration is successful, the replication potential is very important.

8.3.2 Winisk Project

Winisk is a remote community located on the south shore of Hudson Bay, Ontario. As part of an Ontario Minstry of Energy initiative, the Ontario Ministry of Natural Resources installed a 10-kW Bergey wind turbine in conjunction with a 10-kW diesel generator and cycle-charged 500-A-h battery storage system at their park headquarters at Winisk. This project is one of the first demonstration of a state-of-the-art WECS/Diesel/Cycle-Charged

System in the north and will provide enough information on performance and operational characterisitics to extend the application of additional small wind turbine systems in the north and in other regions of Canada where conventional energy sources have high costs.

8.3.3 The Sinnott Installation - TransAlta Utilities Monitoring

In early 1984, an Alberta farmer, A.E. Sinnott, erected on his farm in Pincher Creek a 40-kW Enertech Wind turbine generator connected to the electric system of TransAlta Utilities Corporation. After several differences between the two parties, a landmark decision was taken by the Energy Resources Conservation Board (ERCB), to establish the concept of energy "banking", over a five-year trial period ending in 1989. During the trial period, Mr. Sinnott will be allowed to "bank" his excess wind generated energy in the TransAlta system and receive credit for it. He will then be able to draw on that credit by taking energy from the TransAlta system during periods of low or zero wind. The balance is computed on a quarterly basis and any net energy supplied to Mr. Sinnott, by TransAlta, is billed at normally applicable TransAlta rates. If, on a quarterly basis net energy is supplied to TransAlta from the wind turbine, it would be paid for by TransAlta at a lower rate. The lower rate would recognize those costs that TransAlta can avoid by purchasing Mr. Sinnott's surplus energy, including avoided fuel costs and transmission line losses.

The trial period ending December 1989 has been set up to obtain technical and cost information on the operation and interaction of the wind generator with TransAlta.

In March 1985, the second monitoring summary was submitted by TransAlta. Three interconnected Small Power Producer (SPP) wind turbine generators were connected to the grid were monitored during the year, viz.

- 5-kW Enertech Wind Generator, Carston
- 5-kW Enertech Wind Generator, Pincher Creek
- 40-kW Enertech Wind Generator, Pincher Creek

Based on gross generation, the three wind generators operated at an average capacity factor of 28.6% during 1985. Capacity factor is the ratio of actual energy generated in a period to the potential energy that could have been generated had the facility operated as its rated capacity over the entire period. Over the year, the average resource availability was 54.0%, i.e., the percentage of the time that wind conditions were suitable for wind generator operation. Average TransAlta equipment availability at the SPP sites was 99.9%. Average SPP equipment availability was 83.9%.

In July 1989, the ERCB will review the findings from the trial period and revise its policy in accordance with those findings.

9.0 CURRENT STATUS OF CANADIAN WIND ENERGY CONVERSION SYSTEMS TECHNOLOGY

Wind energy research and development in Canada has focussed on the vertical axis wind turbine. Wind energy R&D programs in Europe have concentrated on the more traditional horizontal axis wind turbine, and in many nations recent work has been structured around existing SWECS industries. In the United States the dominant effort has been toward large-scale HAWTs, although very significant work on VAWTs has been supported by the U.S. Department of Energy through the Sandia National Laboratories and in a few major firms.

In the period from 1980 to 1985 wind energy R&D in most countries followed two parallel paths. Relatively small-scale equipment (~50 kW) could be put into production quickly and strong interest in alternative energy sources precipitated many major demonstration projects, the most dramatic concentration being in California where over 15 000 such units were installed in the five-year period. Simultaneous with this effort to gain operational experience, research on much larger units was underway in response to techno-economic studies which showed improving cost-effectiveness with increasing unit size up to several megawatts rated power. Sweden, Germany, United States, United Kingdom, and Canada embarked on multimegawatt WECS prototype projects.

In general, the results of these different approaches to wind energy technology have proven to be mutually compatible. At present, HAWT technology is more mature than VAWT technology because of strong American and European research efforts, ready adaptability of certain aerodynamic and structural analysis techniques for propellers and helicopter rotors, and an existing foundation of HAWT design philosophy from prewar applications. Nevertheless, VAWT technology is now generally accepted as showing equal promise of good performance and some potential for a slight cost-effectiveness advantage. The two configurations represent two viable embodiments of wind energy technology, each with understandable pros and cons when considered for any given application.

The development of both HAWT and VAWT megawatt-scale machines has proved more costly and more time-consuming that initially anticipated. "Second guess" studies still indicate that "bigger is better" for commercial production equipment; however, the resources required to achieve technical maturity may be beyond justification in today's economic scenario of falling oil prices and utility overcapacity. Under such conditions it is most important to glean as much engineering information as possible from existing megawatt-scale prototypes in order to provide a sound basis for future developments.

9.1 Performance

No work has been done at NRC on techniques to predict aerodynamic performance of HAWT rotors although a general appreciation of the methodology and results exists among aerodynamacists in the Low Speed Aerodynamics Laboratory.

Curved blade Darrieus VAWT rotor performance analyses are quite advanced at NRC (and also at SNL in the United States and elsewhere). Accuracy of aerodynamic performance prediction in the installed operating regime depends primarily on the accuracy and completeness of airfoil characteristic data. Lift and drag curves must be known for much wider ranges of angle of attack than for most aeronautical applications. Considerable experience is also needed to account for the drag of rotor components other than the blades (e.g., struts, closed spoilers, joints, bolt-heads, etc.). Such aspects are usually accounted for in the choice of C_{d_0}, the drag coefficient of the blade airfoils at zero lift. This parameter is quite sensitive and small charges can significantly affect the predicted cut-in wind speed. Nevertheless, prediction of VAWT power curves below stall-controlled limits is possible within acceptable engineering accuracy using techniques such as those described in Section 5.1.

Aerodymanic phenomena during stall-limited-power operation of VAWTs are very complex. Traditional quasi-steady-state airfoil stall characteristics are totally inadequate for accurately predicting stall-limited-power, usually underestimating maximum power by as much as 25% (see Section 5.1.2). This phenomenon is caused by the dynamic nature of the stall experienced by the VAWT blade. The angle of attack changes cyclically as the rotor spins, and both separation and reattachment of the flow are delayed beyond their quasi-steady-state values. This introduces an asymmetry into the torque-angular position curve for the rotor. Some efforts have been made at NRC to measure these dynamic stall characteristics on an NACA0018 airfoil section moving cyclically under computer control in the NAE 2 m × 3 m wind tunnel (A-54) and also analytically (A-44). Beyond the determination of dynamic airfoil characteristics it is necessary to account for the dynamic effects in the VAWT rotor performance prediction routines. Various attempts to do this by Templin (A-43), Parishivov (F-9), and others have met with some limited success. Certainly, more research is required to fully understand these phenomena and then to accurately describe them within the computer programs for performance curve predictions.

In addition to the WECS power curve, prediction of energy yield of a given system at a specific location requires knowledge of the site wind required. As outlined in Chapter 2 the speed and temporal distributions of wind strongly affect energy yield. Even if accurate wind data are available for

the site from specific or general meteorological measurements, the year-to-year variation in wind regime may influence annual energy output predictions as much as uncertainties in the WECS power curve. Certainly, if the site wind regime must be estimated from geographically distant data, these uncertainties will far outweigh the likely inaccuracies in WECS power curve estimation.

9.2 Structural Integrity

Though not addressed in the Canadian wind energy R&D program, the structural behaviour of HAWT blades has been analyzed extensively within American and European programs. Considerable applicable lore was available from propeller and especially helicopter rotor technology. Such features as flexibeam pitch control, teetered hubs, and damped delta-three hinge configurations have been incorporated in many HAWTs.

Again, the Canadian program has concentrated on the curved-blade Darrieus VAWT configuration. Major analytic research on the structural dynamic behaviour of such rotors was performed at the Sandia National Laboratories in New Mexico, U.S.A. Many of the programs now used by Canadian VAWT researchers and manufacturers are derivatives of the fundamental SNL analyses which comprise pre- and post-processors to adapt the VAWT problem to very powerful generalized structural analysis programs such as NASTRAN. These techniques, though complex, are highly developed and, provided with a sufficiently detailed physical description of the rotor, will produce mode and frequency data within engineering requirements. Extensions of this analysis method have been made at Indal Technologies Inc. to include the aerodynamic forcing functions and the resulting stress patterns in the rotor structure and guy wires.

A particular concern relating to all structural elements of both HAWTs and VAWTs is fatigue. Many significant loads in both configurations are cyclic (recall Section 4.3.3), and the high capital cost of WECS demands great longevity to assure long-term cost effectiveness. A 100-kW WECS rotating at 75 rpm for 5000 hours per year will experience over 1.5×10^9 major stress cycles during a 25-year design life. Many data acquisition routines used to monitor prototype WECS have "Rainflow" counting subroutines which keep track of the expenditure of fatigue life during engineering evaluation and early operational phases. As in the case of aerodynamic performance prediction, many of the basic data needed in the structural dynamic analyses and fatigue life prediction programs are difficult to obtain. Few well-documented data are available on fatigue limits of WECS blade materials at 10^9 cycles. For large WECS no truly appropriate design codes exist to guide the designer in vital issues such as allowable loads in materials or joint fastners. As a case in point, ÉOLE's bolted steel blades

were designed to codes intended for bridges, plus the good judgement of the design team.

9.3 Systems Engineering

A WECS, whether VAWT or HAWT, is a combination of aerodynamic, structural, mechanical, electrical, and electronic components. It is axiomatic to note that the combination must be designed as a cohesive entity if optimum performance and cost effectiveness are to be achieved. The major systems engineering decisions are related to the matching of rotor, end-form energy conversion device, load, and wind regime. Clearly, optimization of even this number of parameters is difficult, if not impossible, without tailoring each design to its particular site and use. Some flexibility can be achieved by the choice of gearbox ratios to match rotor characteristics to site winds.

Different generator ratings can be used with a given rotor to relate power loading to site wind regime. The recent introduction of power electronics (e.g., SFC) to couple nonstandard generator output to grid networks has significantly enhanced the scope for programmable controllers to tailor the WECS to its site and load.

Rudimentary techniques exist (mainly within WECS manufacturers' engineering departments) to address this systems engineering issue. Such analyses might be considerably enhanced by adaptation of systems engineering methodology from other fields such as hydraulic powerplant technology.

The wind/diesel hybrid powerplant is a particularly strong candidate for systems engineering expertise. In addition to the diesel generator, the WECS, the load, and the wind speed, incorporation of energy storage into the system adds another parameter to the optimization procedure. Preliminary experimental work in Canada, the United Kingdom, and the United States has shown that steady-state diesel economy curves apply even though the diesel-generator must provide the power difference between the rapidly fluctuating WECS' output and the generally more steady load. Thus, it is feasible to create a quasi-steady-state routine that accepts wind speed and load as functions of time and computes fuel consumption from known diesel generator and WECS performance curves. Such programs exist in the public domain (E-33) and also in many WECS manufacturers and energy application consultant firms. Such programs usually incorporate provisions for storage and hence provide convenient means to assess various combinations of system components and sizes. Fuel savings computed by such systems engineering programs can then be used in financial analyses to assess the economic viability of the candidate configuration.

As mentioned in Section 4.3.4, there is also a need for systems engineering in windpump design. For example, the choice of bore and stroke of a reciprocating pump can significantly affect cut-in wind speed and annual water delivery, especially in modest wind regimes. Systems analysis programs, similar to those described above for wind/diesel electric powerplants, need to be written and verified against experimental data.

9.4 Controls and Protection Systems

The controls for grid-coupled electrical VAWTs with induction generators are relatively simple and many WECS manufacturers had developed reliable systems. Controls for HAWTs are somewhat more complex with additional parameters such as yaw and blade pitch to account for. Some near-disasters have occurred when prototype controllers fail to respond to circumstances beyond their design scope and/or when components malfunction. Designed-in redundancy of vital functions, internal self-checks, and plug-in diagnostic simulators all contribute to confidence in control system function.

There is considerable need for further development of control and protection systems for wind/diesel powerplants, especially those incorporating energy storage. Research "test-beds" such as the wind/diesel facility at RISØ, Denmark, and the one being installed at the AWTS in Canada usually incorporate Programmable Logic Controllers to provide the flexibility to explore different control strategies. Analytical simulation routines (E-34 to E-37) that can realistically reproduce transient behaviour of wind-diesel-storage systems are complex and require considerable experience to operate and to interpret the results. Nevertheless work on such dynamic models must continue as experimental cut-and-try development is too dangerous, too costly, and too slow.

Most current windpumps have only the most rudimentary controls - adequate to protect the machine but seldom capable of any sort of optimization. It is also axiomatic that windpump controls must be self-activating, requiring no electricity or external inputs beyond those from the windpump itself.

Traditional windpumps had little to control; pump stroke is the obvious candidate parameter for any attempt at optimization (e.g., DELTX WP50). However, if hydraulic or pneumatic drivetrains prove cost-effective and reliable there will be greater scope for simultaneously optimizing the operating conditions of rotor and pump.

9.5 Reliability

Good WECS technology is inherently reliable. Both HAWTs and VAWTs are relatively simple machines (compared to a gas turbine engine or a hay baler, for example) comprising relatively few parts, many of which are current

production items for other applications. Nevertheless, to be cost-effective most WECS must operate automatically, unattended, with infrequently scheduled maintenance, and for a lifetime of two or three decades.

As with most new technology, two factors conspire to create many failures in prototype hardware. The first factor is lack of understanding of all the ramifications of a new technology. For example, until analytical methods were developed to predict resonant modes and frequencies, early prototypes suffered premature low cycle fatigue, sometimes with dramatic consequences. The second factor is more insidious; it is simply the commission of blunders that happen because the entire chain of designers, builders, erectors, and operators are dealing with new methodologies for which there are no handbooks or past experience to fall back on.

The Canadian 50-kW field trial projects (see Section 7.4) began amid many frustrating minor failures (and one or two catastrophies). Spoilers stuck, electrical relays attracted salt water, controllers didn't, bolts worked loose, bearings failed for no reason, lubrication pumps overheated in summer and froze in winter, etc., etc. Yet in few of these instances was there cause to question the basic design concepts. As of December 1985, most of the 50-kW VAWTs have accumulated over 15 000 h of operation and consistently achieved over 90% availability. Much early unreliability was caused by lack of appreciation of the ravages of even moderate climates. Corrosion is the bane of WECS designers - structural, mechanical, and electrical engineers alike. Also, the remote and one-off nature of most early demonstration projects contributed to long shutdown periods for even relatively newer faults.

Reliability requires an extended proving period. It is significantly quicker and easier to demonstrate improved performance than to demonstrate improved reliability. Hence in early stages of operation it is wiser to concentrate on accumulating running hours than to focus on defining the top end of the power curve. In most cases, failure to operate accounts for far more uncaptured energy than poor performance.

Some current Canadian WECS have established creditible reliability records (e.g., ITI 50, 500-kW VAWT) while others offer promise that is yet to be demonstrated (e.g., ADSCON 125, 150 kW; DELTX WP 50).

Among all phases of nurturing a new technology from concept to commercialization, the achievement of acceptable and consistent reliability requires the greatest support and perseverence. Unfortunately, this demanding phase is seldom studded with dramatic achievements and is often the most difficult to adequately finance, falling between research programs and programs to help commercialize a proven product. Nationally subsidized test

facilities such as AWTS and LWTS can play an important role in this vital process, providing constant human and/or electronic monitoring and experienced staff to interpret the data.

9.6 Operating and Maintenance Requirements

Most WECS must be designed to operate automatically, unattended, and with only infrequently scheduled maintenance. Ideally, annual servicing is performed during low wind periods preceding the windiest season.

There are few data on long-term maintenance requirements of Canadian WECS beyond those related for the 50-kW VAWT field trial projects reported in Section 7.4. Individual Canadian WECS installed in the United States and overseas have functioned satisfactorily but detailed maintenance records are not available. In experimental and some demonstration projects maintenance of the monitoring equipment is more demanding than maintenance of the equipment under test.

The skills required to commission and maintain a production WECS are somewhat different, but in no way more sophisticated than those required by an automobile mechanic. A not-insignificant technical and financial requirement in commercializing any WECS is the creation of comprehensive manuals covering installation, commissioning, troubleshooting, and maintenance of the system.

10.0 COST EFFECTIVENESS OF WIND ENERGY

Cost-effectiveness, not efficiency, nor engineering sophistication, is the ultimate goal of the WECS designer/manufacturer. High efficiency and/or complicated configurations and controls can only be justified if increased energy yield exceeds increased cost. On a 10-m diameter HAWT, adding 0.5 m to each blade will increase energy yield by about 20% and may well be considerably cheaper than increasing system efficiency by 20%. With "free fuel," maximizing efficiency loses its traditional appeal in favour of improving cost-effectiveness.

The cost-effectiveness of any wind energy conversion system depends on four major factors:

- the wind regime at the site
- the performance of the WECS
- the installed cost of the WECS
- the projected operational/financial scenario

The significance of the wind regime and the performance of the WECS have been discussed in Chapter 4. This chapter discusses WECS capital and operating costs and techniques by which the cost effectiveness of candidate WECS sites may be assessed.

10.1 Wind Energy Conversion Systems Costs

The annual cost of a WECS installation comprises two elements, viz:

- the cost of ownership - which reflects the initial capital cost of the complete WECS system and the annual interest charged, or rate of return demanded

- the operating and maintenance (O&M) cost - which includes inspections, repairs, and consumables (such as oil) plus all labour costs including transportation of personnel and replacement parts to the site.

These values differ greatly from installation to installation, depending not only on the site and the WECS hardware, but also on the perceptions of the assessor or owner. Enthusiasts tend to downplay both the costs of ownership ("once the windmill is paid for, the energy is free") and O&M costs ("it doesn't cost a penny to run, I look after it myself"). On the other hand, industrial/utility users quantify all costs, including even corporate overhead charges. The analysis presented here is taken from reference A-30 and provides for reasonable reference flexibility in choosing between these philosophies.

10.1.1 Capital Costs

The capital cost of a WECS installation is the sum of the following costs of:

- the complete WECS unit, f.o.b. the factory
- delivery to the site
- provision of site access
- foundations and supporting structure
- assembly and erection
- interconnection to the load
- commissioning and check-out

For preliminary economic analyses it is common to represent all other elements of the installed system cost as a percentage of the WECS f.o.b. factory costs. The value of this "installation" percentage can vary significantly with the type, number, and size of the WECS, as well as with the location and topography of the site. For hundred-unit wind farms on relatively flat, accessible terrain, installation costs could be as little as 25% of WECS f.o.b. factory cost. For a single unit requiring crane erection at a rugged isolated site, the cost for installation, connection, and commissioning could exceed the WECS f.o.b. factory cost.

10.1.2 Wind Energy Conversion Systems Cost per Unit Area

A common parameter used to specify installed cost of generating systems is "dollars per rated kilowatt." This is not appropriate for WECS because, for a given size rotor, different WECS manufacturers may install generators with quite different rated powers (i.e., different power loadings). However, in a given wind regime the amount of energy produced is much more dependant on rotor size than on generator rating. Thus, a more meaningful unit for expressing installed cost for WECS is dollars per unit of swept area ($\$/m^2$).

10.1.3 Operating and Maintenance Costs

The annual operating and maintenance (O&M) costs for a complete WECS system include costs of

- insurance premiums, licence fees, etc.
- rental of land, connection equipment
- periodic inspections and routine maintenance
- consumables (e.g., oil, grease, etc.)
- replacement parts and labour for repairs

Such costs are often expressed as a percentage of the WECS hardware costs; this reflects the typically minimal maintenance requirements of site preparations, foundations, and interconnection systems. However, for the present analysis, it is convenient to express annual O&M costs as a fraction of total installed system costs, choosing, of course, appropriately lower numerical percentages to reflect the greater base value.

10.2 Economic Calculation Methods

10.2.1 Fixed Charge Rate Economics

The total annual cost of the WECS system is the sum of the cost of ownership and the cost of O&M. If both these costs are expressed as fractions of the total initial capital cost of the installed and commissioned WECS, one can write

[9] Annual Cost (AC) = (FCR + O&M)Capital Cost

where

FCR = the fixed annual fraction of the initial total system capital cost (CC) required to amortize the debt at interest rate i in n years

$$= \frac{i(1 + i)^n}{(1 + i)^n - 1}$$

and

O&M = the levelized annual operating and maintenance cost expressed as a fraction of the initial capital cost of the complete installation (CC)

The cost of energy can be found by dividing the annual cost of owning and operating the equipment (AC) by the annual net energy output (AE)

$$[10] \qquad COE = \frac{(AC)}{(AE)} = \frac{(FCR + O\&M)\ (CC)}{(AE)}$$

which, expressed in units common to electrical generation systems, is

$$[11] \qquad ¢/kWh = \frac{(FCR + O\&M)\ CC}{kWh/a} \times 100$$

Three scenarios might be chosen and values of the Annual Cost Factor (FCR + O&M) computed as follows:

Optimistic:	i = 8%,	n = 30 a,	O&M = 1%,	ACF = 0.0988
Neutral:	i = 12%,	n = 20 a,	O&M = 2%,	ACF = 0.1539
Pessimistic:	i = 16%,	n = 10 a,	O&M = 3%,	ACF = 0.2369

The inverse of the Annual Cost Factor can be used as a rough guide to the **allowable** total capital cost of a WECS system to provide a given cost of energy. For example, assuming the NEUTRAL scenario, (FCR + O&M) = 0.1539, and hence the allowable installed cost of a WECS to produce energy valued at D $/a is $(D ÷ 0.1539). If the energy value D were $1000/a then the WECS must be purchased and installed for $6500. Similarly, if an Optimistic or Pessimistic scenario was postulated, the allowable installed cost would be $10 100 or $4200, respectively.

10.2.2 Present Value Analysis

Economic assessment by Present Value Analysis is a more rigorous method of evaluating, as a function of time, cumulative costs and benefits in terms of the current value of money and a prescribed discount rate. Such analyses were performed on a number of WECS by Barclay and Oliver of EMR (F-7).

The Cost of Energy or Fixed Charge Rate is a simple technique for assessing the cost of electricity produced by a candidate WECS, so that a prospective owner may quickly determine the likely financial viability of such an installation, and may appreciate the relative importance of the major parameters which will affect its performance. Indeed, this simple method of assessment could well indicate the desirability of more sophisticated economic and performance analyses.

10.3 Wind Energy Conversion Systems Cost Effectiveness

Considering the roughly optimum power loadings for various average wind speeds as developed in Chapter 4, and the economic relations developed above, one can create a map of wind energy cost as a function of average wind velocity for a variety of different WECS unit costs as shown in Figure 29.

Also shown on Figure 29 are three scales giving energy costs in ¢/kWh corresponding to the installed cost per annual unit energy output for the three economic scenarios chosen somewhat arbitrarily in Section 10.2.1.

WECS manufacturers' brochures usually include values of rated power, rotor diameter, and f.o.b. factory cost. Installed WECS unit cost can therefore

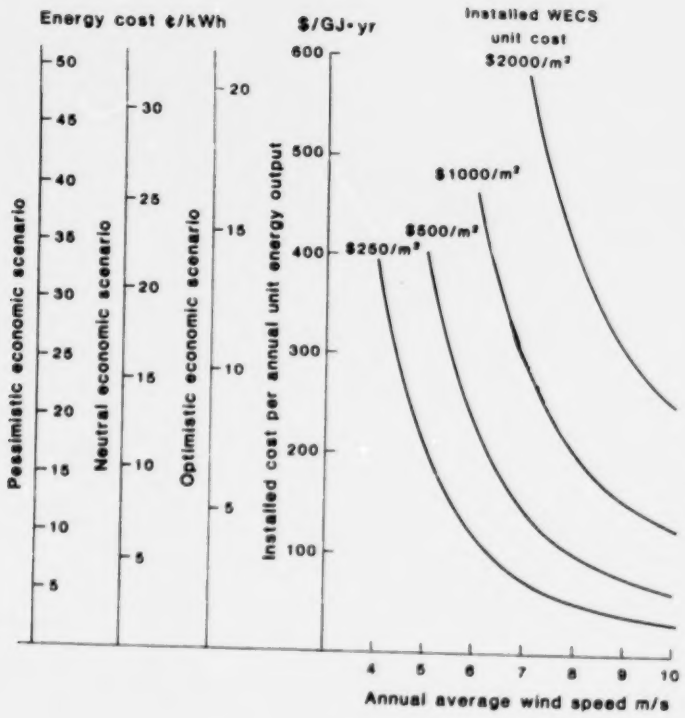

Figure 29. WECS energy costs

be determined by multiplying f.o.b. cost by an appropriate factor to account for transportation, installation, connection, and commissioning costs, and then dividing by the swept area computed from the blade diameter or other rotor geometric data. The appropriateness of power loading for the site under consideration should be checked by dividing the maximum power rating by the swept area and comparing the quotient to the values suggested in Section 4.3.2. If the power loading seems appropriate (and if the candidate turbine is well designed) the cost of energy from the proposed installation can be read from the chosen economic scenario opposite the intersection of the Installed WECS Unit Cost curve and the Annual Average Wind speed of the candidate site.

Example

Consider a Brand X wind turbine rated at 15 kW, with a 25-foot diameter rotor, that costs $20 000 f.o.b. the factory. The proposed site has an annual average wind velocity of about 6 m/s.

(i) Estimate installed/commissioned cost as being 1.75 × factory cost, i.e., $38 500.

(ii) Compute swept area

$$A = \frac{\pi}{4}\left(\frac{25}{3.28}\right)^2 = 45.6 \text{ m}^2$$

(iii) Compute installed WECS unit cost

$$\text{Unit Cost} = \frac{38500}{45.6} = \$844/\text{m}^2$$

(iv) Check power loading

$$\text{Power Loading} = \frac{15000}{45.6}$$

$$= 328 \text{ W/m}^2 \text{ (which is satisfactory for 6 m/s)}$$

Then from Figure 29

Installed Cost per Annual Unit Energy Output		= \$390/GJ•a
Cost of Energy:	Optimistic Scenario	= 13.5¢/kWh
	Neutral Scenario	= 22¢/kWh
	Pessimistic Scenario	= 33¢/kWh

Note that the allowable annual O&M costs inherent in the three economic scenarios are \$385, \$770, and \$1155 for the Optimistic, Neutral, and Pessimistic scenarios, respectively.

The foregoing considerations can be combined into a single multiparameter plot and nomograph as shown in Figure 30. The graph on the right-hand side summarizes performance of current typical well-designed WECS, including the frequently quoted Plant Factor which defines the fraction of rated power that is produced on average by the candidate WECS in the wind regime under consideration. The four nomograph scales on the left describe the economic factors, including continuously variable scales for the annual cost factor and the capital cost per unit swept area. These scales are used by drawing straight lines between the A and B scales, and between the B scale and the ordinate scale of the performance plot (marked C).

The use of the Wind Turbine Performance and Cost Effectiveness Chart is best explained by example, as on Figure 30. From manufacturer's data, estimates of installation costs, knowledge of site winds, and perception of economic conditions the following input values are established:

$$P_{max}/A = 500 \text{ W/m}^2$$
$$V_{ave} = 8 \text{ m/s}$$
$$\text{Installed cost} = \$500/\text{m}^2$$
$$\text{Economic Scenario} = \text{Neutral}$$

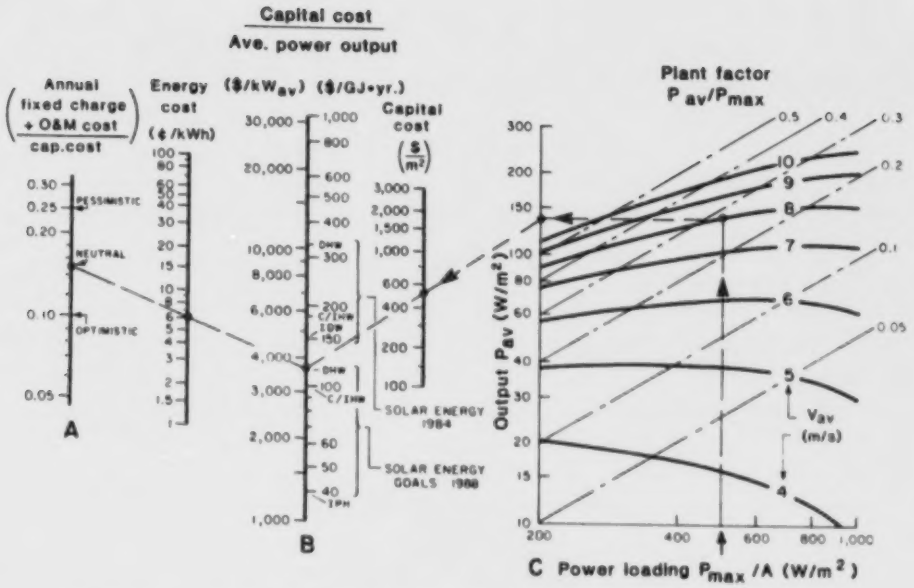

Figure 30. Wind turbine performance and cost-effectiveness chart.

The performance plot is entered at a power loading of 500 W/m^2. Going up to the 8-m/s wind speed line indicates a Plant Factor of 0.28 and an Average Unit Power Output of 140 W/m^2. It can also be noted that at 500 W/m^2 the power loading of the candidate windmill is somewhat below optimum, as increasing the power loading to 800 W/m^2 (say by purchasing the "optional higher-rating model for very windy areas") increases P_{av}/A to 150 W/m^2 (from 140 W/m^2) even though Plant Factor reduces to 19% (from 28%).

Projecting a straight line from 140 W/m^2 on performance scale C through the $500/$m^2$ Installed Capital Cost nomograph line gives a capital cost per unit average power output of $3700/$kW_{av}$ or $120/GJ•a on line B. Presuming the Neutral economic scenario with a corresponding Annual Cost Factor of 15%, one can obtain the cost of energy (6¢/kWh) by joining the appropriate points on lines A&B.

The following general observations concerning WECS cost effectiveness can be made from Figures 29 and 30.

- The strong dependence of energy output on annual average wind speed can be noted from the performance plot of Figure 30 despite the use of a logarithmic ordinate scale which results in the higher wind-speed curves being closer together. This sensitivity justifies careful site selection and consideration of tower height. Appropriate choice of power loading for a given wind regime is seen to be more important for poor or very good sites and less critical for moderate wind regimes with 5 to 6 m/s annual average wind speed.

- For any given average power output it can be seen that Plant Factor is strongly dependent on power loading. High power loading tends to result in relatively short periods of high power output, whereas low power loading may give the same average power (and hence the same energy output) but in longer periods of somewhat lower power production. This "output power spectrum" is of considerable importance if the wind system rating is a substantial fraction of the total generation capacity, or if the application involves energy storage.

- The linear relation of the total capital cost of the installed WECS to system cost-effectiveness is self-evident from Figure 29. Expressed in other terms, however, halving the installed capital cost reduces the annual average windpseed required to achieve a given level of cost-effectiveness by 1 to 2 m/s. It is interesting to note the consequent fact that an uncertainty of 1 to 2 m/s in site average wind speed gives the same doubt in economic viability as not knowing the system capital cost to within a factor of two.

- The effect of the presumed O&M and financial scenario is seen directly from the slope of the line drawn between nomographs A and B on Figure 30. Although often difficult to quantify, the longevity, interest rate, and O&M parameters must be carefully and realistically chosen in order to predict meaningful costs.

11.0 INTERNATIONAL WIND ENERGY TECHNOLOGY

All industrialized countries have on-going research and development programs in wind energy technology. Many belong to one or both of the International Energy Agency Implementing Agreements, viz.

- R&D WECS Research and Development on Wind Energy Conversion Systems
- LS WECS Large-Scale Wind Energy Conversion Systems

The National Research Council represents Canada on both these collaborative agreements which provide our primary window on activities in foreign countries. Other major participant nations include United States, United Kingdom, Sweden, Germany, Denmark, and the Netherlands. Recently, the European Economic Community has allocated substantial funds for cost-shared wind energy projects in member states.

11.1 Denmark

In Denmark small-scale wind energy technology is well advanced into the commercial stages. Most units from the half dozen major manufacturers are currently 50- to 80-kW HAWTs, although several models of 100 to 300 kW have reached the preproduction stage. There are about 1000 individual 10-50-kW WECS installed and connected to Denmark's electric grid, offsetting owners' electricity costs and selling surplus power to the utilities. Denmark has the most advanced infrastructure for wind turbine manufacturers (all belong to a formal association, there is one blade supplier for most commercial units, etc.) and also for users (owners' groups that provide meaningful experience feedback to suppliers, etc.).

Danish WECS Standards are well advanced, and the national WECS testing station (RISØ) tests and licences all new models, thereby granting eligibility for mortgage and insurance coverage, as well as government subsidies.

The Danish wind power program for development of large-scale, electricity-producing wind energy conversion systems (LS WECS) was initiated in 1977, and its main objective is to investigate under what circumstances and to which degree wind energy can make a viable contribution to the Danish electricity supply system. The program is sponsored jointly by the government and the electric utilities, and the work is done by utility personnel, public institutions, and Danish industry. DEFU acts as a coordinating agency.

The Danish wind resources are fairly well described in the report *Wind Atlas for Denmark* (F-11). The siting possibilities within Danish territory with regard to large-scale WECS have been the topic of a general

siting investigation. A detailed grid integration study was completed in 1983. It showed that in the long run there may be problems with "surplus energy" produced by wind turbines and perhaps also load-following problems at times with rapid changes in wind velocity once penetration became a significant fraction of grid supply.

At present, most efforts are concentrated on technology development. Two aspects are predominant. The first is to overcome the various fatigue problems encountered in wind turbines, the second is to reduce the specific installation costs to a level which would make wind power more cost effective and, thereby, eventually more competitive with electricity produced in conventional power plants.

To address these aspects, two 40-m diameter, three-bladed, 630-kW HAWTs were erected at Nibe in Jutland. To date the Nibe A unit has operated for about 5700 h and Nibe B for about 10 100 h. Information from these tests is being incorporated into the design study of a 60-m diameter, 2.0-MW commerical unit for the Jutland electric utility, to be erected at Esbjerg with partial support from EEC.

ELKRAFT Power Company Ltd., the regional power company of Zealand, has undertaken a demonstration project comprising five 40-m diameter, three-bladed 750-kW units manufactured by Danish Wind Technology Limited. The site for this wind farm is on Masnedo at Vordingborg on the south coast of Zealand.

Several other intermediate-scale WECS are being installed by Danish regional electric utilities. Also, the Danish government is sponsoring extensive research into wind/diesel systems at RISØ, primarily for export markets.

11.2 Germany

The German wind energy program is focussed on development of large-scale grid-coupled HAWTs. The 100-m diameter, two-bladed, 3.0-MW prototype GROWIAN, located near Kaiser-Wilhelm-Koog, is physically the largest wind turbine in the Western world. Serious structural problems discovered during early running have limited testing. Nevertheless, much useful experience has been gained and will be incorporated into the WEK 60-m diameter, 1.2-MW unit to be installed on the island of Helgoland as part of a 3.6-MW wind/diesel total energy package. MONOPTEROS, located near Bramerhaven, is a 370-kW model of a 145-m "diameter", single-bladed, 5-MW HAWT that has not yet received formal approval for construction. Meanwhile, the local utility at Wilhelmshaven has undertaken to support a cluster of three 1-MW versions of MONOPTEROS, built by MBB.

Studies of the realistic potential for LS WECS predict that up to 12% of German electricity consumption (300 TWh/a in 1980) could economically be provided from wind turbines by the year 2000. Even if the speed and intensity of actual exploitation is only one-sixth of this forcast, a market for over 300 WECS of 1-3 MW rating and many thousands of smaller units is expected. Already M.A.N. - Neue Technologie has exported 350 AEROMAN 40- and 100-kW HAWTs to California. Germany also has cooperative wind energy projects with Spain, including research on a "solar-chimney" WECS, incorporating a 250-m diameter sun cover beneath which heated air rises toward a 200-m-high chimney housing a 10-m diameter WECS. This 75-kW prototype model, located at Manzamares, is used to provide parametric data to corroborate design estimates for giant 10-100-MW systems. Germany and Spain have also proposed joint development of a "Megawatt Class AWEC 60" for participatory funding by the EEC.

11.3 Italy

Wind energy R&D began in the early 1980's directed by the Italian state-owned utility Ente Nazionale per L'Energia Elettrica (ENEL). Though wind speeds are modest over most of mainland Italy, Sardina and other islands and coastal regions offer potential for cost-effective wind energy applications.

Early efforts focussed on small HAWTs with rated powers of up to 70 kW. FIAT and Aeritalia developed 13-m diameter prototypes which were evaluated at the national WECS test facility at Santa Caterina. Engineering research, wind tunnel experiments, and small-scale field trials were undertaken by several universities (Torino), private industries (Ansaldo, Aeritalia, SES, AGIP) and public instutions (CNR, CNEN, ENEL). Both HAWTs and VAWTs were examined for generation, pumping, and heating applications. In particular Agip Nucleare have experimented with an 8-kW model of a 100-kW VAWT-diesel system.

A wind farm comprising ten 50-kW FIAT was built in 1984 at Alta Nurra, Sardinia and another 10-unit wind farm to be located in Southern Sicily is being discussed. Also at Alta Nurra, a 32-m diameter, two-bladed, 225-kW HAWT prototype will be commissioned in the summer of 1986.

Feasibility and preliminary design of a 70-m diameter 2.0-MW HAWT was completed by Aeritalia and FIAT Aviazone under contract from ENEA/ENEL. Negotiations for siting and funding a prototype unit are underway.

11.4 Japan

Japan relies heavily on foreign oil for energy to supply its industry. The Sunshine Project was started in 1974 to explore the basic tenets and

develop technology relating to renewable energy sources, including wind energy. The program forsaw the realistic time requirements to commercialize new technology. Starting in 1981, 15 years were allocated to development of practical wind energy systems of intermediate and large scale. The program is managed by the Ministry of International Trade and Technology (MITI).

Wind resource potential has been estimated at 17 TWh/a, displacing between 5% and 10% of Japanese oil-fired electrical supply.

Many small experimental WECS were built by several Japanese companies for exploring electrical, air compressing, pumping, and heating applications and were tested at various sites in northern, western, and southern Japan. Mitsubishi installed and tested a 18-m diameter, three-bladed, 40-kW HAWT for Kyushu Electric at Negasaki. Fatigue failure of the rigid hub necessitated a revision of design philosophy to the soft-tower, soft-rotor configuration later incorporated in Mitsubishi's 33-m diameter 300-kW system.

A 29.4-m diameter, two-bladed, 100-kW experimental HAWT was constructed on Miyakejima Island, about 180 km south of Tokyo. This unit incorporated an ac-dc-ac link to achieve grid-compatible power output.

11.5 The Netherlands

The first phase of the Netherlands National Wind Energy R&D Program (NOW) ran from 1981 to 1984 and cost 58.6 M Dfl. of which 12.6 m Dfl were provided by Dutch industries and utilities. During 1985 reviews and evaluations were carried out, leading to a follow-up program for 1986-1990. Support is primarily from the Ministry of Economic Affairs with participation from the electric utility companies, EEC, and other Dutch Ministries. The Dutch government has adjusted its official goal concerning the contribution of wind energy to the national energy supply in the year 2000. In its official reaction towards the Public Discussion on Energy Policy, the government states that 1000 MW of installed wind power can be realized; wind energy is considered as the most important among available renewable energy sources. The major part of this 1000 MW will consist of large-scale systems.

Currently, about five Dutch manufacturers are providing series production small- and intermediate-scale WECS for domestic and export applications. Polenko, Holec, and FDO have made significant sales to California wind farm entrepreneurs.

Large-scale WECS development is founded on basic research and operating experience with the 25-m two-bladed, 300-kW HAT experimental wind turbine gathered by the Netherlands Energy Research Foundation (ECN) at the

national WECS test facility in Petten. Over 12 500 h of operation have been logged. Stork-FDO Wind Energy Systems have produced and installed three NEWECS 25 commercial systems based on the HAT. Stork-FDO have recently completed a prototype NEWECS 45 scale-up, comprising a 45-m diameter, two-bladed rotor and an ac-dc-ac electrical system rated at 1.0 MW. The machine is located near Medemblik in North Holland and is owned and operated by the provincial utility PEN. Plans are formed to proceed to a larger and more advanced unit, the 80-m diameter, two-bladed, 3-MW GROHAT. Certain structural and aerodynamic innovations are being explored on the 25-m HAT before finalizing the design of the 80-m prototype.

Near the village of Sexbierum in the north of the Netherlands, an experimental wind farm comprising 18 Holec 300-kW machines is being realized. The total cost of about Dfl 60 million is shared by the Joint Utilities (SEP) and the Ministry of Economic Affairs on a 50%-50% basis.

11.6 Sweden

An evaluation of the Swedish wind energy program was published in early 1985 (F-10). The program started in 1975 and had cost about 270 million Swedish kronor in public funding up to the end of 1984. The main activities have been directed to the design and construction of the two large-scale prototypes at Maglarp and Näsudden. An assessment of the national wind resources has been made, and the possibilities of siting wind power plants were investigated in relation to wind conditions and environmental impact. A program of basic research was carried out at universities, industrial firms, and other research institutes.

The basic research program is coordinated and to a large extent performed by FFA, the Aeronautical Research Institute of Sweden. The activities include development of analytical methods, wind tunnel testing, structures and materials analysis and testing as well as safety and environmental issues.

The wind prospecting carried out by the Swedish Meteorological and Hydrological Institute showed that the two best wind classes comprise about 4000 km^2 along the west coast, in the province of Skane, and on the island of Ocland and Gotland in the Baltic Sea. Discounting densely populated areas, holiday housing areas, military ranges, etc., these regions could theoretically accommodate about 30 TWh/a of wind power generation. By identifying other pronounced land use interests it is concluded that an annual energy production of about 10 TWh can be obtained in the best and second-best areas with minor conflicting interests.

The large-scale prototype HAWT at Maglarp was designed by Hamilton-Standard in the United States and, with the exception of the wound-filament fiberglass blades, was built in Sweden. The 78-m diameter, two-bladed, 3.0-MW machine has been operated by the Sydkraft utility since September 1983, during which time it has generated 10 GWh in 6400 h running. Recent availability is over 70%, with most unscheduled outages caused by sensor malfunctions.

The second megawatt-scale prototype, located near Nassudden in southern Gotland, was designed and built by KaMeWa in Sweden with fiberglass blades from ERNO in Germany. The 75-m diameter, two-bladed, 2.0-MW HAWT has been operated by the state Power Board since 1983. Following an early gearbox failure the unit has accumulated 4000 hours and generated 4.4 GWh. Current availability is about 60%.

It was concluded that experience with the two prototypes (owned by the National Energy Administration) confirms the feasibility of building and operating large wind power units. The plants were found to be generally well designed with regard to real load situations and technical environment. Great attention was devoted to safety and environmental aspects. Accident risks were found to be small, but the plants have a significant impact on the landscape. The wind turbines cause a mechanical noise from the rotor that under certain conditions is audible at 500-1000 m distance from the plants. The thumping noise from the downwind Maglarp turbine can sometimes be perceived up to 2 km from the plant. The disturbance of TV reception which arose in the neighbourhood of the Maglarp turbine could be remedied by installing a small slave transmitter. The energy bill adopted by the parliament in June 1985 calls for further efforts to develop wind energy in Sweden. The activities include:

- a continued national program of basic research and development, amounting to 67 million Swedish Kronor for the three-year period 1984-1987

- a siting study to be completed in 1987 aiming at proposing group station sites for a total generation of 10 TWh/a on-land and about 20 TWh/a offshore. The first phase to be reported in late 1986 will comprise sites for a total generation of 5 TWh/a, preferably on-land

- a development program for the period 1985-1987 tentatively amounting to 42 million Swedish Kronor, half of which will be contributed by the utilities and half by the government (included in the above-mentioned 67 MSEK). The program includes:

  - installation of a medium-sized (~1-MW) wind turbine
  - conceptual study of a large unit

- continued operation, evaluation, and modification of the Maglarp and Näsudden prototypes

In order to carry out the development program, a new company has been formed by the utilities. The owners are the State Power Board (50%), the Sydkraft utility (25%), and the Swedish Power Association (25%).

11.7 United Kingdom

In the United Kingdom, wind energy is stated to be the most promising of all renewable energy alternatives. Both the Department of Energy and the Central Electricity Generating Board (England's national electric utility) are supporting development and demonstration of large-scale WECS. Studies have shown that up to 10% of Britain's electricity supply could be provided by multimegawatt wind turbines, primarily located offshore in the shallow waters surrounding the island.

Major projects have been initiated by the North of Scotland Hydro Electricity Board (NOSHEB) in the Orkney Islands where average wind speeds on hilltops are about 10 m/s. The Wind Energy Group (WEG - a consortium of Taylor Woodrow and British Aerospace) have erected a 20-m diameter, two-bladed, 250-kW HAWT on Burgar Hill, Orkney. This machine is a one-third-scale model of a 60-m, 3.0-MW HAWT now under construction and slated for erection at the same site in 1986. The Wind Energy Group, with support from the EEC, developed a commercial variant of the 20-m machine on Orkney. The first of these 25-m diameter, three-bladed, 200/250-kW systems was installed at Ilfracombe and connected to the South West Area Electricity Board distribution grid in 1984.

With cooperation from NOSHEB, James Howden & Co. Ltd. of Glascow installed a 22-m diameter, three-bladed, 300-kW HAWT next to the WEG model on Burgar Hill, Orkney. Each of the Orkney prototypes has now operated for over 6000 h, with early teething problems but recently with acceptable reliability. The commercial embodiment of the initial Howden machine is a 26-m diameter, three-bladed, 330-kW unit that has been exported to Barbados, California, and elsewhere. A smaller 15-m diameter, three-bladed, 60-kW Howden wind turbine is being marketed for use in isolated communities (e.g., Fort Severn, Canada) and for wind farm applications in California. A larger 45-m diameter, three-bladed 750-kW prototype is being built with EEC financial support for installation in the Shetland Islands in 1986. Several of these units are also scheduled for erection in Howden's California wind farms.

UKDOE and CEGB are also supporting development of a variable geometry VAWT based on the arrowhead concept of Prof. Musgrove at Reading University.

VAWT LTD (a consortium of Sir Robert McAlpine, Hawker Siddeley, and NE Cranes Ltd.) are under contract to erect a 25-m diameter, 200-kW prototype system at Carmarthan Bay. As follow-on to this project a preliminary design study of a multimegawatt VGVAWT has been initiated.

UKDOE also sponsors generic wind energy research activities including studies of materials and fatigue, structural dynamics and aeroelasticity, aerodynamics and performance, as well as costs, economics, and off-shore potential. The UK national wind turbine testing facility has been established at the National Engineering Laboratories in East Kilbride near Glasgow. Other significant technical activities and facilities exist at certain universities (e.g., Reading, Oxford Rutherford Appleton Laboratories) where considerable research on wind/diesel/storage systems is underway.

In addition to hosting demonstration intermediate and large-scale WECS, the CEGB play a lead role in several IEA R&D WECS activities relating to turbine/network interaction, resource/potential studies, environmental effects, and offshore WECS technology.

11.8 United States

The United States federal wind energy program was initiated by the Energy Research and Development Agency (ERDA) in 1973. Today it is directed and funded by the Department of Energy (USDOE). It has focused on large-scale HAWTs, but during the past five years has paid significant attention to VAWTs, especially in regard to basic research towards the understanding of fundamental aerodynamic and structural dynamic behaviour and the creation of effective design tools.

A series of large HAWTs has been supported by USDOE. Following the 100-kW experimental MOD-0 erected at Plum Brook in 1975, four 200-kW derivatives (MOD-0A) were installed and evaluated in grid-connected service with local utilities. The 2-MW MOD-1 installed at Boone, North Carolina, in 1979 was the first modern megawatt-scale HAWT and provided much useful data for future designs. After having served their purpose of providing design, construction, and operating experience, the MOD-0A and the MOD-1 machines were closed down and dismantled. The MOD-0 unit continues its experimental role, currently being used to determine the response characteristics of a one-bladed rotor.

Five second-generation MOD-2 2.5-MW units have been built by Boeing and are currently operated by two utilities and a federal agency. A group of three such units in Goodnoe Hills, Washington, has logged over 10 000 machine-hours, generated over 13 GWh, and is providing the first full-scale data on interactions among these large machines. Hamilton-Standard has built two

large-scale HAWTs: a 4-MW unit at Medicine Bow, Wyoming (on the same site as one of the MOD-2 units), and a 3-MW machine at Maglarp, Sweden.

Boeing are now developing the third-generation MOD-5B rated at 3.2 MW and scheduled for erection in Hawaii later this year.

The motivation towards larger unit sizes (MOD-5B was originally 7.2 MW) is the projected improvement of cost-effectiveness. However, the development of megawatt-scale WECS is proving to be slower and more expensive than originally anticipated. The major unforseen problems are not related to concept, but to detail engineering of very large machinery and the consequent cost and time required to fund and effect the inevitable repairs.

In parallel with the large-scale HAWT demonstrations, USDOE is supporting substantial R&D effort in VAWT technology. The majority of this work is managed and conducted by the Sandia National laboratories (SNL) in Albequerque, New Mexico. Understandably, close relations have been maintained between VAWT research engineers at SNL and at NRC, Canada. Several hundred intermediate-scale VAWTs built by Flowind Corp. are now operational in California. Late in 1986 SNL will commission a 32-m test-bed turbine to investigate advanced aerodynamic and structural dynamic aspects of megawatt-scale VAWTs. This large experimental unit will enhance the substantial analytic and experimental results that have come from the SNL 5-m and 17-m research VAWTs.

The evolution of wind farms in the United States during 1981-1985 has been phenomenal, especially in California (see Section 11.8.1). Commercial grid-coupled wind farms are also operational in Vermont, Massachusetts, and Hawaii. A combination of financial and strategic ramifications of increased oil price and vulnerability of supply, and of federal and state tax incentives, has greatly accelerated the normal evolution and deployment of the emerging wind energy technology. This is particularly true of the California situation as described in the following subsection.

To be viable in the long term, wind-generated electricity will have to demonstrate parity with electricity from other sources. To guide the American program's efforts toward establishing the technology base needed for viable wind technology, long-term (1990) technical goals have been established, and these are summarized in Figure 31. The technical goals were derived based on extensive studies of the economic value or benefit of wind-generated electricity to specific electric utilities. A review of these studies indicates that electricity costs in the range of 3¢ to 4¢/kWh (in constant 1984 dollars) would establish wind technology as a viable energy supply option. Thus, 4¢/kWh was selected as a appropriate target for wind turbines installed in the mid-1990s, although 3¢/kWh is probably

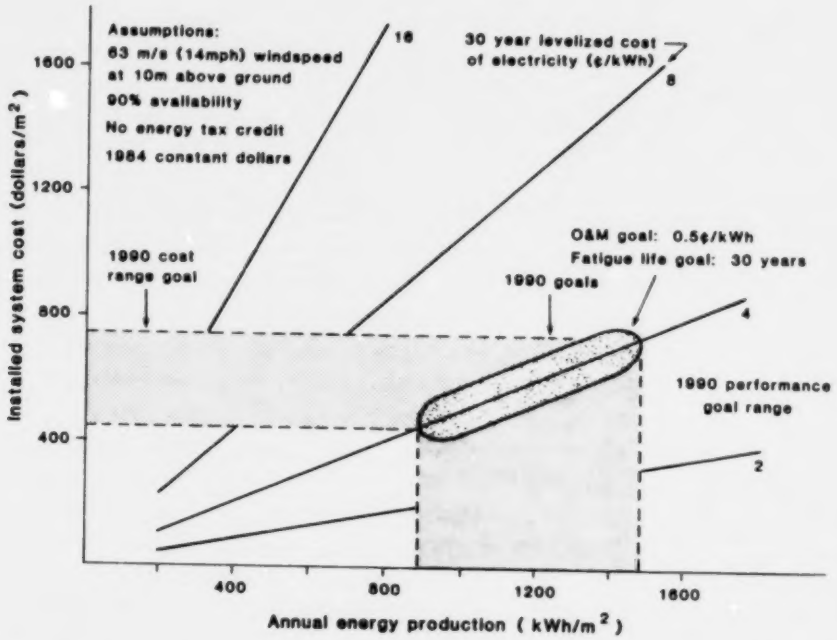

Figure 31. Five-year goals for wind energy technology R&D in the United States (after a figure in "Windpower: Five-Year Research Plan 1985-1990," U.S. Department of Energy, January 1985).

required for the longer term. The derivation of this target and of the technical goals is explained in detail in Appendix II of reference F-12.

11.8.1 The California Windrush

The speed and extent of WECS deployment in California during the early 1980's is a unique phenomenon precipitated by the following circumstances:

- PURPA: the U.S. Federal Public Utility Regulatory Policies Act which requires electric utility agencies to purchase electricity from alternate energy sources at "avoided cost"

- FEDERAL TAX CREDITS: whereby investors in wind farms can claim 10% investment tax credit, plus 11% energy investment credit for the full value of the installation

- STATE TAX CREDITS: providing an additional 25% investment tax credit in California (similar or smaller credits were available in many other states)

- RAPID DEPRECIATION: allowing depreciation of wind energy equipment over five years

- GOOD WIND REGIME: strong on-shore winds created by the proximity of desert and ocean separated by mountains. The winds are also correlated to energy demand - both increasing in hot sunny weather.

- PREDOMINANTLY OIL-FUELED UTILITIES: providing strong financial and strategic motivation to seek alternate energy sources

In addition to these specific regulatory and technical circumstances, two other features added to the attractiveness of Southern California for wind farm developers. A relatively high proportion of highly paid people could take advantage of the tax credits, and large expanses of poor quality open land (mainly used for cattle grazing) could be leased at reasonable cost for wind farming. Indeed, most land so leased is still used for grazing cattle who do not seem the least perturbed by the wind turbines.

The majority of California wind farms are located in the passes inland from major load centers such as Los Angeles and San Francisco (see Figure 32).

Table 12 lists the numbers and aggregate rating of WECS installed in California during the period from early 1981 to the end of 1985, based on data published by the California Energy Commission.

Figure 32. California wind farm locations.

Figure 33 illustrates the rapid growth of Californian windfarms and lists some statistics of the size and cost of the WECS units comprising these projects.

Table 12. California Wind Energy Installations

Area		1981/2	1983	1984	1985	Total
Altamont Pass	Units	804	1179	2040	2531	6554
	MW	46	90.1	201.5	254.6	592.2
San Gorgonio Pass	Units	10	651	1465	2285	4411
	MW	1.6	36.8	89.5	204.6	332.5
Tehachapi Pass	Units	464	652	999	2814	4929
	MW	21.0	44.7	88.9	262.4	417.0
Other Areas	Units	11	7	101	1082	1201
	MW	2.7	0.3	6.0	76.1	85.1
Total	Units	1289	2489	4605	8712	17095
	MW	71.3	171.9	385.9	797.7	1426.8

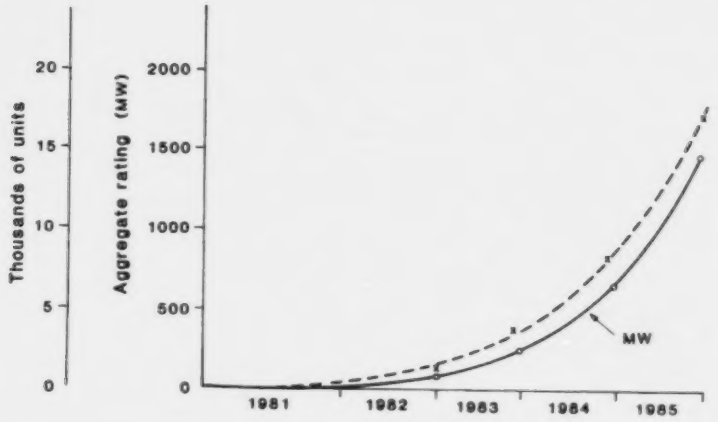

Figure 33. California wind farm projects.

	1981	1982	1983	1984	1985	Total
Average Unit Rating	49kW	56	69	84	92	
Average Project	1MW	5	7	10	17	
No. Projects (CUM)	5	19	44	82	130	
Average Cost ($84 US)	3113$/kW	2175	1900	1860	(1750)	
Capital Inv. ($84 US)	21.8M	139.9	326.6	717.8	1396	2.6B

The reactions to provisions of substantial financial incentives for evolving technology are clearly manifest in the California experience. During the early period of the incentives many immature systems were installed resulting in poor reliability, little energy generation, and huge repair and rectification requirements. Indeed, as shown in Table 13, it was not until 1984 that overall Plant Factor rose above 5%.

Table 13. California Wind Energy Production

Year	Inst'd MW(com)	MWh produced	Plant factor[1]	Revenue @ 8¢ 1 kWh
1981	7	10	<0.1%	$800.00
1982	71	4 800	1.9%	0.38M
1983	243	47 400	4.2%	3.8M
1984	629	188 100	5.8%	15.1M
1985	1427	600 000	7.7%	48.0M

[1] $\text{Plant factor} \equiv \frac{\text{MWh(produced)}}{8760 \times \text{MW (installed)}} \times 100\%$

and

$$\text{MW (installed year n)} \equiv MW_{n-1} + (1/3)(MW_n - MW_{n-1})$$

where the factor 1/3 presumes units installed during year n are fully operational for only 4 months

Maturity and reliability have increased steadily since then but still fall significantly short of the technically achievable target of about 20% Plant Factor. Quantity production and increased experience have reduced installed costs by a factor of about two during the five-year period; however, further cost reductions are likely to be minor. Further improvements in cost-effectiveness will be achieved by increasing energy yield (primarily by increasing reliability) and by the installation of larger units for future wind farms and/or retrofits. It should be noted that early unit sizes of around 50-kW rated power were selected on the basis of availability rather than system optimization. Current installations are typically 100 to 500-kW units as these, at present, are the largest commercially available units on the market. The emphasis however, remains on improving reliability, and the proportion of Netherlands and Danish systems being imported has grown markedly in the past three years, reflecting the domestic "track record" of these machines.

The California Energy Commission predicts that by 1990 WECS will be 10% of the installed generating capacity and will provide 2% of the total electric energy supply. The abolition of the federal tax credits in 1986 may well retard this level of penetration, but there is no doubt that aeroelectricity will play a major role in the Californian energy mosaic from now on.

12.0 OPPORTUNITIES AND PRIORITIES FOR CANADIAN WIND ENERGY TECHNOLOGY

12.1 Domestic Opportunities

Canada is blessed with an abundance and a variety of energy sources. Virtually every traditional energy resource is available somewhere in Canada, usually at attractive cost, though sometimes requiring transportation over significant distances to reach major load centers. Hence, to contribute to major Canadian energy networks, wind energy must compete with some of the cheapest end-form energy costs in the world. For example, domestic consumers in major Canadian centers pay an average of about 5¢/kWh for electricity.

Consequently, barring some unforseen disruption to normal price trends, it is not likely that wind energy will provide a measurable fraction of Canadian national energy supplies at least until the end of the century. Continued refinement of the technology, especially with respect to reliability and cost effectiveness, will eventually enable wind energy to compete with traditional network supplies in certain regions of Canada, principally the Maritime provinces. The evolution of major regional wind energy supplies will be inhibited by lack of commitment for the level of effort required to develop very large machines, notwithstanding general acceptance that cost-effectiveness improves with increasing unit size.

In the near term, significant market opportunities exist in areas of Canada remote from the major energy distribution networks. There are over 800 diesel generator sets with an aggregate rating of over 500 MW providing power to more than 300 Canadian communities that are not connected to major power grids. Individual sets range from <50 kW to >1 MW rating, and a typical single community or local powerhouse comprises three to six sets. Real electricity prices range from 15¢/kWh to over $1.00/kWh, although consumer rates are often subsidized. Many of these locations have moderate to excellent wind regimes, though most lack ready access to the variety and size of construction equipment required for erection of large WECS. Hence, intermediate-scale WECS, of the order of a few hundred kilowatts rating, have good potential in these areas. Economics of candidate installations are judged primarily on fuel savings but, as experience grows, some capacity credit may be justified in the future.

A few special opportunities now exist in Canada for wind farms to provide significant contributions to the electrical supplies of major near-shore islands. Perhaps the most attractive example is Iles de la Madeleine where 60 MW of diesel generators supply the domestic and industrial needs of about 15 000 people. The average wind speed on Iles de la Madeleine is over 8 m/s. Other potentially attractive Canadian wind farm sites include Prince Edward Island and the Queen Charlotte Islands.

The pacing factor in development of these near-term domestic markets is equipment reliability. Diagnosis and repair of unfamiliar equipment is a serious perceived risk in the consideration of such projects. The Remote Communities Demonstration Program (Section 8.1.3) is designed specifically to address this issue.

In addition to community electricity supplies there are thousands of small autonomous power systems in the remote regions of Canada, powering individual dwellings, nursing stations, communications relay stations, navigational aids, automatic weather stations, and similar demands. These loads typically average a few hundred watts to a few killowatts; the smaller ones often incorporate battery storage. Small-scale WECS are readily incorporated into such systems, but again reliability in unattended operation is of paramount concern.

Major agricultural initiatives to extend arable land area and increase crop productivity often require either irrigation and/or drainage. Windpumps have traditionally played a major role in such applications where small non-time-dependant power supplies are needed beyond economical extensions of grid networks. Here, the tradition is reliability and the challenge is to improve performance and also to increase size to intermediate-scale WECS suitable for centralized irrigation pumping stations. In a related area recent interest in the preservation (or indeed production) of wetlands for breeding waterfowl has provided another near-term domestic market for modern windpumps.

12.2 Export Opportunities

Near-term export opportunities closely match near-term domestic opportunities, viz. autonomous and hybrid electric powerplants and wind pumpers. Emphasis on proven reliability, usually manifest by successful domestic installations, is even greater in the export market. Canada is significantly behind the United States and several European countries in mass-production of intermediate-scale WECS. Thus we do not yet have the proven reliability nor the operational experience needed to realistically address export markets. Once early experience demonstrates initial reliability, foreign aid agencies such as CIDA may present a means to broach the vast but unquantified market for appropriate wind energy technology in developing countries.

In the long term, export of large-scale Canadian VAWT technology is a possibility, but viability will depend almost entirely on private sector willingness to continue development of megawatt-scale systems.

12.3 Priorities

Current priorities for further development of Canadian wind energy technology are focussed toward the small/intermediate systems for both electrical and pumping applications. These priorities are:

- improve reliability
- improve cost-effectiveness
- improve system engineering

The objective of development is to get more end-form energy from a given environment for a given investment. At the moment, kilowatt-hour production by Canadian WECS is limited by hours of operation, not by power conversion efficiency. As reliability, and hence operating hours per year, increase, long-term structural integrity (e.g., fatigue life) will also be important.

Once system reliability has reached about 85% availability, then consideration must be directed towards system optimization. Factors such as component efficiency trade-offs, matching power loading to wind regime, and other systems engineering issues discussed in Section 4.3.2 must be re-examined.

Underlying both these aspects is the critical third dimension of cost. As in most emerging technologies, use of standard components, well proven and mass produced for other uses, will enhance the cost-effectiveness of early commercial WECS. In second or third generation products, however, the incorporation of more more-optimal specialized components may be worthwhile.

Sophistication, which is often manifest as complication, is seldom economically attractive, especially in small units. A variable-stroke controller may well be justified for a million-dollar intermediate-scale irrigation windpump, but not on its farm-scale sibling.

13.0 CONCLUDING OBSERVATIONS AND RECOMMENDATIONS

During the past decade Canadian wind energy technology has made enormous strides, expecially in understanding the nature and extent of the resource, in deducing the aerodynamic and structual characteristics of the VAWT, and in creating the basic design tools for commercial systems. From a modest laboratory project within NRC's Low Speed Aerodynamics laboratory has grown an infrastrucutre of technically knowledgeable manufacturers and users well able to appraise the potential of wind energy under most circumstances. Major potential users have been sensitized to significant parameters affecting wind energy viability, and many have acquired hands-on experience through joint field trial projects. A start toward real experience with megawatt-scale VAWTs has been made and is expected to continue under private sector auspices.

On the less positive side Canada's predominant leadership in VAWT technology of the mid-seventies has diminished in the mid-eighties. In the United States, researchers at Sandia National Laboratories have enjoyed substantial government support for in-house basic research and have extended and refined many of the fundamental analyses developed at NRC. Substantial operating experience with hundreds of intermediate-scale VAWTs in California wind farms has been an expensive but effective development tool. Nevertheless, Canada retains a strong competence in VAWT technology, both within NRC and within firms such as Indal Technologies and Adecon Energy Systems. The latter firm has made some dramatic advances in VAWT cost-effectiveness which, once field proven, will exceed US DOE goals for 1990. It is axiomatic that these areas of strength should continue to be supported.

Another piece of innovative Canadian engineering is manifest in the delta-blade windpump being developed by ABAX Energy Services in Calgary. Sucsessful demonstration of this equipment will gain eligibility to not only domestic irrigation applications, but also to foreign and export markets. Its simplicity and ease of fabrication from a variety of materials should make it most attractive for indiginous production in developing countries.

As discussed in Cnapter 12, the near-term opportunities for Canadian VAWT technology are forseen as being small/intermediate-scale units for supplying electricity for isolated applications and to remote communities. The current priorities are for improved reliability, cost-effectiveness, and ultimately more optional system engineering. With these points in mind, the following recommendations are made for continued evolution of Canadian wind energy technology.

1. Wind energy technology development in Canada should continue to focus on the intermediate-scale VAWT for electricity generation. Side-band

activity should maintain awareness of HAWT state-of-the-art. Continued development of megawatt-scale VAWT technology with private sector participation will establish technical and economic guide posts for future exploitation of this scale of WECS.

2. Because near-term domestic applications are believed to be in remote communities, an inventory should be made of all significant non-grid-connected settlements, their true electricity costs, and their wind regimes. A rating scheme could then identify locations and/or regions of greatest wind energy viability. Demonstration projects would then be targeted into these areas.

3. A concerted effort should be made to orchestrate a viable Canadian wind farm project using Canadian technology. Necessary participants would include a realistic user (utility), Canadian WECS manufacturer(s), technical and industrial support agencies, and independant technical monitors/reporters.

4. Strong support should be directed towards continued development and proving of Canadian WECS hardware that has particular potential for near-term commercialization. The performance advantage of the delta-blade windpump and the operational reliability of the low-cost VAWT should be an identified thrust in the immediate future.

5. When the delta-blade windpump concept is proven at field-test scale, a specific effort should be made in cooperation with CIA to enhance its local produceability in third world countries.

6. Effective standards (including load cases) for detailed design and quality control should be established and implemented by the Canadian WECS industry. Efficacy should be monitored in terms of reliability of Canadian WECS hardware.

7. A major system engineering exploration should be made of wind/diesel/storage systems to supply isolated communities. Load characteristics, wind energy fractions, and effects of storage capacity (and inflow/outflow rates) on system cost-effectiveness are but three of the major parameters to be examined.

8. Short-term energy storage mechanisms for absorbing torque ripple and momentary excess power from wind gusts should be studied for improved quality of power, especially for application to wind/diesel hybrid generating systems.

9. A better understanding of structural dynamics and structural fatigue of wind turbine rotors should continue to be developed in order to more accurately predict fatigue life and to identify design and operating characteristics which impact fatigue life.

10. Better, yet simpler, control systems should be developed for wind turbines to reduce unnecessary shut-downs and to ensure adequate protection of both aerogenerator and load, and smooth synchronization with the electrical grid.

11. Simpler-to-use analytical tools should be developed for the wind turbine designer that relate turbine performance to local topography and wind regime.

14.0 REFERENCES

14.1 National Research Council Reports

A-1 P. South, R.S. Rangi
PRELIMINARY TEST OF A HIGH SPEED VERTICAL AXIS WINDMILL MODEL
Laboratory Technical Report LTR-LA-74
National Research Council of Canada, Ottawa, Ontario
March 1971

A-2 P. South, R.S. Rangi
A WIND TUNNEL INVESTIGATION OF A 14 FT. DIAMETER VERTICAL AXIS WINDMILL
Laboratory Technical Report LTR-LA-105
National Research Council of Canada, Ottawa, Ontario
September 1972

A-3 P. South, R.S. Rangi
THE PERFORMANCE AND ECONOMICS OF THE VERTICAL-AXIS WIND TURBINE DEVELOPED AT THE NATIONAL RESEARCH COUNCIL, OTTAWA, CANADA
Presentation at the 1973 Annual Meeting of the Pacific Northwest Region of the American Society of Agricultural Engineers
October 1973

A-4 R.S. Rangi, P. South, R.J. Templin
WIND POWER AND THE VERTICAL AXIS WIND TURBINE DEVELOPED AT THE NATIONAL RESEARCH COUNCIL
Reprint of Article from DME/NAE Quarterly Bulletin No. 1974(2)
National Research Council of Canada, Ottawa, Ontario
May 1974

A-5 R.J. Templin
AERODYNAMIC PERFORMANCE THEORY FOR THE NRC VERTICAL AXIS WIND TURBINE
Laboratory Technical Report LTR-LS-160
National Research Council of Canada, Ottawa, Ontario
June 1974

A-6 P. South, R.S. Rangi
AN EXPERIMENTAL INVESTIGATION OF A 12 FT. DIAMETER HIGH SPEED VERTICAL AXIS WIND TURBINE
Laboratory Technical Report LTR-LA-166
National Research Council of Canada, Ottawa, Ontario
April 1975

A-7 R.J. Templin
AN ESTIMATE OF THE INTERACTION OF WINDMILLS IN WIDE-SPREAD ARRAYS
Laboratory Technical Report LTR-LA-171
National Research Council of Canada, Ottawa, Ontario
June 1974

A-8 G.J. Klein
THE DESIGN OF HIGH-SPEED WINDMILLS SUITABLE FOR DRIVING ELECTRIC GENERATORS (Revision of Report No. PAA-32, Ottawa, June 14, 1937)
Laboratory Technical Report LTR-LA-183
National Research Council of Canada, Ottawa, Ontario
August 1975

A-9 R.J. Templin, P. South
CANADIAN WIND ENERGY PROGRAM
Prepared for delivery at the Vertical Axis Wind Turbine Technology Workshop held in Albuquerque, New Mexico
May 18-29, 1976

A-10 R.J. Templin, P. South
SOME DESIGN ASPECTS OF HIGH-SPEED VERTICAL AXIS WIND TURBINES
Proc. of the International Symposium on Wind Energy Systems, Cambridge, England
September 7-9, 1976

A-11 J.R. Amyot, R.E. Gagne, R.J. Templin, R.S. Rangi
MACDALEN ISLANDS WIND TURBINE HYBRID COMPUTER MODEL
Proc. of the Summer Computer Simulation Conference, Chicago, Illinois
National Research Council of Canada, Ottawa, Ontario
July 1977

A-12 P. South, A. Watts
MAGDALEN ISLANDS VAWT FIELD TEST
Paper presented at the U.S. Dept. of Energy Workshop "Operational and Economic Status and Requirements of Large Scale Wind Systems", Monterey, California
March 1979

A-13 R.J. Templin
DESIGN CHARACTERISTICS OF THE 224 KW MAGDALEN ISLAND VAWT
Paper presented at the U.S. Dept. of Energy "A Workshop on Large Wind Turbine Design Characteristics and R&D Requirements"
NASA/Lewis Research Centre, Cleveland, Ohio
April 1979

A-14 P. Waudby-Smith
PERFORMANCE MEASUREMENTS OF A STRAIGHT-BLADED, VARIABLE PITCH VERTICAL AXIS WIND TURBINE
Laboratory Technical Report LTR-LA-236
National Research Council of Canada, Ottawa, Ontario
July 1979

A-15 W. Wiebe, D.D. Morphy
FAILURE ANALYSIS OF A MORSE MG600A CLUTCH FROM THE SUDBURY WIND-DIESEL TEST SITE
Laboratory Technical Report LTR-ST-1426
National Research Council of Canada, Ottawa, Ontario
November 1982 (PROPRIETARY)

A-16 W. Wiebe, R.V. Dainty
FAILURE INVESTIGATION OF A STEEL FLEXIBLE COUPLING FROM THE VAWT AT CHURCHILL, MANITOBA
Laboratory Technical Report LTR-ST-1393
National Research Council of Canada, Ottawa, Ontario
May 1982

A-17 W. Wiebe, A.C. Walker, R.V. Dainty
NON-DESTRUCTIVE INSPECTION OF THE HOLYROOD VERTICAL AXIS WIND TURBINE
Laboratory Technical Report LTR-ST-1392
National Research Council of Canada, Ottawa, Ontario
June 1982

A-18 W. Wiebe, D.D. Morphy
FAILURE INVESTIGATION OF DAF (6 m × 9 m) VERTICAL AXIS WIND TURBINE - ATLANTIC WIND TEST SITE
Laboratory Technical Report LTR-ST-1492
National Research Council of Canada, Ottawa, Ontario
February 1984 (PROPRIETARY)

A-19 J.J. Kacprzynski
A MODIFIED FFEVD SANDIA PROGRAM FOR NASTRAN FREQUENCY RESPONSE ANALYSIS OF VERTICAL AXIS WIND TURBINES
Laboratory Technical Report LTR-ST-1568
National Research Council of Canada, Ottawa, Ontario
January 1986

A-20 R.V. Dainty, D. Chow
INVESTIGATION OF VAWT (AQUILO) "A" BLADE FAILURE AT THE ATLANTIC WIND TEST SITE, PEI
Laboratory Technical Report LTR-1582
National Research Council of Canada, Ottawa, Ontario
March 1986

A-21 R.J. Templin
EFFECT OF DESIGN PARAMETERS ON WIND TURBINE PERFORMANCE
Wind Energy Technical Memorandum TM-WE-001
National Research Council of Canada, Ottawa, Ontario
January 1981

A-22 P.J. Penna
TESTING AND CALIBRATION OF THE DAF-INDAL LTD. WIND HISTOGRAM
Wind Energy Technical Memorandum TM-WE-002
National Research Council of Canada, Ottawa, Ontario
January 1981

A-23 S.L. Bocso
WIND ENERGY RESOURCE ASSESSMENT SEMINAR (WERAS 80)
Wind Energy Technical Memorandum TM-WE-003
National Research Council of Canada, Ottawa, Ontario
November 1980

A-24 E. Whiteley (under contract to NRC)
PRELIMINARY STUDY TO COMPARE DARRIEUS WIND TURBINE SYSTEMS WITH GEAR-DRIVEN ALTERNATORS TO SYSTEMS WITH DIRECT-DRIVEN ALTERNATORS AND STATIC FREQUENCY CONVERTERS
Wind Energy Technical Memorandum TM-WE-004
National Research Council of Canada, Ottawa, Ontario
November 1980

A-25 M.S. Chappell
THE CANADIAN WIND ENERGY RESEARCH & DEVELOPMENT PROGRAM: OVERVIEW AND CURRENT STATUS
Wind Energy Technical Memorandum TM-WE-005
National Research Council of Canada, Ottawa, Ontario
August 1981

A-26 R.J. Templin, R.S. Rangi
MEASUREMENTS ON THE MAGDALEN ISLAND VAWT AND FUTURE PROJECTS
Wind Energy Technical Memorandum TM-WE-006
National Research Council of Canada, Ottawa, Ontario
October 1981

A-27 M.S. Chappell
THE WIND PROGRAM IN CANADA
Wind Energy Technical Memorandum TM-WE-007
National Research Council of Canada, Ottawa, Ontario
October 1981

A-28 R.J. Templin
AN APPLE II PROGRAM FOR COMPUTING WINDMILL PERFORMANCE
Wind Energy Technical Memorandum TM-WE-008
National Research Council of Canada, Ottawa, Ontario
January 1982

A-29 P.J. Penna
WIND TUNNEL TESTS OF THE THERMAX HELIUS AND SAVONIUS ROTORS
Wind Energy Technical Memorandum TM-WE-009
National Research Council of Canada, Ottawa, Ontario
May 1982

A-30 M.S. Chappell, R.J. Templin
ASSESSMENT OF PERFORMANCE AND COST EFFECTIVENESS OF WIND ENERGY CONVERSION SYSTEMS
Wind Energy Technical Memorandum TM-WE-010
National Research Council of Canada, Ottawa, Ontario
October 1984

A-31 M.S. Chappell
THE WIND ENERGY RESEARCH AND DEVELOPMENT PROGRAM IN CANADA
Wind Energy Technical Memorandum TM-WE-011
National Research Council of Canada, Ottawa, Ontario
March 1982

A-32 G. Krishnappa, T.H. Hammel
NOISE AND VIBRATION MEASUREMENTS OF 50 kW VAWT GEARBOX IN VICTORIA, B.C.
Wind Energy Technical Memorandum TM-WE-012
National Research Council of Canada, Ottawa, Ontario
August 1982

A-33 GasTOPS Limited
COMPUTER PROGRAM FOR AERODYNAMIC ANALYSIS OF VERTICAL AXIS WIND TURBINE
SUMMARY REPORT
Wind Energy Technical Memorandum TM-WE-013
National Research Council of Canada, Ottawa, Ontario
November 1982

A-34 M.S. Chappell
CANADIAN WIND ENERGY RESEARCH AND DEVELOPMENT - STATUS AND PERSPECTIVES
Wind Energy Technical Memorandum TM-WE-014
National Research Council of Canada, Ottawa, Ontario
May 1983

A-35 R.S. Rangi
PERFORMANCE OF THE HOLYROOD I 50 kW VAWT
Wind Energy Technical Memorandum TM-WE-015
National Research Council of Canada, Ottawa, Ontario
February 1986

A-36 R.S. Rangi, D. Kimbell
PERFORMANCE OF THE HOLYROOD II 50 kW VAWT
Wind Energy Technical Memorandum TM-WE-016
National Research Council of Canada, Ottawa, Ontario
March 1986

A-37 R.S. Rangi, M.S. Chappell, D. Kimbell
PERFORMANCE OF THE 50 kW VAWT AT CHURCHILL, MANITOBA
Wind Energy Technical Memorandum TM-WE-017
National Research Council of Canada, Ottawa, Ontario
March 1986

A-38 R.S. Rangi, D. Kimbell
PERFORMANCE OF THE CHRISTOPHER POINT 50 kW VAWT
Wind Energy Technical Memorandum TM-WE-018
National Research Council of Canada, Ottawa, Ontario
March 1986

A-39 M.S. Chappell
SOME CURRENT ACTIVITIES IN THE CANADIAN WIND ENERGY PROGRAM
(Presented at the American Wind Energy Association National Conference, 19 October 1983)
Wind Energy Technical Memorandum TM-WE-019
National Research Council of Canada, Ottawa, Ontario
October 1983

A-40 R.J. Templin, R.H. Wickens
AERODYNAMIC CHARACTERISTICS OF AN NACA 0018 AIRFOIL AT HIGH REYNOLDS NUMBERS AND AT ANGLES OF ATTACK FROM 0° TO 180°
Wind Energy Technical Memorandum TM-WE-020
National Research Council of Canada, Ottawa, Ontario
July 1984

A-41 P.J. Penna, J.C. Kuzina
MAGDALEN ISLANDS VAWT SUMMARY AND INDEX OF EXPERIMENTAL DATA: 1980-1982
Wind Energy Technical Memorandum TM-WE-021
National Research Council of Canada, Ottawa, Ontario
October 1984

A-42 M.S. Chappell
STATUS AND OUTLOOK FOR WIND ENERGY RESEARCH AND DEVELOPMENT IN CANADA CIRCA 1984
Wind Energy Technical Memorandum TM-WE-022
National Research Council of Canada, Ottawa, Ontario
December 1984

A-43 R.J. Templin
THE NRC DOUBLE MULTIPLE STREAM TUBE THEORY FOR VERTICAL AXIS WIND TURBINES
Wind Energy Technical Memorandum TM-WE-023
National Research Council of Canada, Ottawa, Ontario
October 1985

A-44 B.G. Newman; (visiting Research Officer)
DYNAMIC STALL FOR VERTICAL-AXIS WIND TURBINES
Wind Energy Technical Memorandum TM-WE-024
National Research Council of Canada, Ottawa, Ontario
March 1985

A-45 G. Krishnappa, J.A. Hammer
BACKGROUND NOISE MEASUREMENTS AT PROJET ÉOLE SITE DURING JULY 1984
Wind Energy Technical Memorandum TM-WE-025
National Research Council of Canada, Ottawa, Ontario
May 1985

A-46 Mechron Energy Limited
AN ANALYSIS OF CYCLE CHARGE AND WIND TURBINE HYBRID POWERPLANTS FOR REMOTE COMMUNITY APPLICATIONS
Wind Energy Technical Memorandum TM-WE-026
National Research Council of Canada, Ottawa, Ontario
March 1985

A-47 J. Keller
LIGHTNING PROTECTION OF WIND TURBINES WITH SPECIAL CONSIDERATION OF VAWTS
Wind Energy Technical Memorandum TM-WE-027
National Research Council of Canada, Ottawa, Ontario
May 1985

A-48 J. Keller
TECHNIQUES FOR MINIMIZING ERRORS IN STRAIN MEASUREMENTS ON WECS ROTORS
Wind Energy Technical Memorandum TM-WE-028
National Research Council of Canada, Ottawa, Ontario
May 1985
Revised June 1986

A-49 PROCEEDINGS OF THE FIFTH INTERNATIONAL MEETING OF TEST STATIONS FOR SMALL WIND ENERGY CONVERSION SYSTEMS: ATLANTIC WIND TEST SITE
Wind Energy Technical Memorandum TM-WE-029
National Research Council of Canada, Ottawa, Ontario
August 1985

A-50 C. Brothers (Atlantic Wind Test Site)
EFFECTS OF WIND SPEED SAMPLING AND AVERAGING INTERVALS ON ACCURARY OF WIND ENERGY ESTIMATES Wind Energy Technical Memorandum TM-WE-030
National Research Council of Canada, Ottawa, Ontario
December 1985

A-51 M.S. Chappell
A PERSPECTIVE ON CANADIAN WINDPUMP TECHNOLOGY
Wind Energy Technical Memorandum TM-WE-031
National Research Council of Canada, Ottawa, Ontario
May 1986

A-52 DAF Indal Ltd.
FURTHER DEVELOPMENT AND TESTING OF THE SUDBURY WIND DIESEL HYBRID POWER PLANT
Wind Energy Technical Memorandum TM-WE-032
National Research Council of Canada, Ottawa, Ontario
March 1985

A-53 A. Watts, M.S. Chappell
PROJECT AEOLUS - PRELIMINARY TECHNICAL DEFINITION
Joint NRC/JREQ Technical Memorandum
31 March, 1981

A-54 R.H. Wickens
WIND TUNNEL INVESTIGATION OF DYNAMIC STALL OF AN NACA 0018 AIRFOIL OSCILLATING IN PITCH
Aeronautical Note NAE AN-27, NRCC No. 24262
February 1985

A-55 P. Penna
A WIND TUNNEL INVESTIGATION OF AEROBRAKES FOR VERTICAL AXIS WIND TURBINES
Proc. Canadian Wind Energy Conference '86
Quebec City, Quebec
October 26-28, 1986

A-56 P. South
A HIGH SPEED VERTICAL AXIS WIND MACHINE
Proc. Advanced Wind Energy Systems Workshop
Stockholm, Sweden
August 29-30, 1974

14.2 Atlantic Wind Test Site Reports

B-1 THE ATLANTIC WIND TEST SITE (Brochure)

B-2 THE ATLANTIC WIND TEST SITE PROSPECTUS

B-3 ATLANTIC WIND TEST SITE BIENNIAL REPORT
December 1981 - December 1983

B-4 K. Slater, M.A. Lodge
EVALUATION OF THE WORTH OF SYSTEM SCALE WIND GENERATION TO THE PRINCE EDWARD ISLAND ELECTRICAL GRID
Paper No. 79051, IEEE Conference & Exposition
1979

B-5 M.A. Lodge
THE POTENTIAL FOR UTILITY SCALE WIND ENERGY IN CANADA
Joint Solar Energy Conference
University of British Columbia, Vancouver, British Columbia
August 1980

B-6 M.A. Lodge
A REPORT ON STUDY RESULTS AND PROPOSED INITIATIVES FOR THE LARGE SCALE INTEGRATION OF WIND ENERGY CONVERSION SYSTEMS IN PRINCE EDWARD ISLAND
Presented to the PEI Energy Corporation
November 1979

B-7 M.A. Lodge
WIND ENERGY PROJECTS AT THE ATLANTIC WIND TEST SITE AND RESOURCE VENTURES INCORPORATED

National Engineering Conference
98th Congress of the Engineering Institute of Canada, Halifax, Nova Scotia
May 1984

B-8 M.A. Lodge
WIND ENERGY PROSPECTING IN PRINCE EDWARD ISLAND: A PROGRAM OVERVIEW AND STATUS REPORT
Second International Symposium on Wind Energy Systems, Amsterdam
October 1978

B-9 ATLANTIC WIND TEST SITE ANNUAL REPORT - 1984

B-10 ATLANTIC WIND TEST SITE ANNUAL REPORT - 1985

B-11 M.A. Lodge, R.G. Richards
BERGEY WINDPOWER BWC-1000 PERFORMANCE SUMMARY
Report #001
Atlantic Wind Test Site, Prince Edward Island, Canada
May 1983

B-12 M.A. Lodge, R.G. Richards
PERFORMANCE INVESTIGATION OF A 17 m × 11 m DARRIEUS TURBINE
Report #002
Atlantic Wind Test Site, Prince Edward Island, Canada
June 1982

B-13 M.A. Lodge, R.G. Richards
INVESTIGATION OF THE FEASIBILITY OF APPLYING SYNCHRONOUS ALTERNATOR/STATIC FREQUENCY CHANGER TECHNOLOGY TO A 17 m × 11 m VAWT
Report #003
Atlantic Wind Test Site, Prince Edward Island, Canada
June 1982

B-14 R.G. Richards
PERFORMANCE TESTING OF A WINDSTAR WS-482-4 WIND ENERGY CONVERSION SYSTEM
Report #004
Atlantic Wind Test Site, Prince Edward Island, Canada
January 1983

B-15 M.A. Lodge, R.G. Richards
DESIGN OF A DRIVE TRAIN AND TESTING EXPERIENCE WITH A 9 m × 6 m DARRIEUS TYPE VERTICAL AXIS WIND TURBINE
Report #005

Atlantic Wind Test Site, Prince Edward Island, Canada
July 1983

B-16 M.A. Lodge, R.G. Richards
AN EXAMINATION OF THE RELATIONSHIP BETWEEN STANDARD AES VELOCITY MEASUREMENTS, ICE ACCRETION AND POWER OUTPUT FROM A WIND TURBINE MOUNTED AT 10M HUB HEIGHT
Report #006
Atlantic Wind Test Site, Prince Edward Island, Canada
March 1982

B-17 H.P. Irwin, M.A. Lodge
WIND SPEED DISTRIBUTION OVER A 1:500 SCALE MODEL OF THE ATLANTIC WIND TEST SITE, NORTH CAPE, PRINCE EDWARD ISLAND
Report #007
Atlantic Wind Test Site, Prince Edward Island, Canada
March 1980

B-18 M.A. Lodge, R.G. Richards
WIND SPEED AND POWER CORRELATION
An Investigation for the Atmospheric Environment Service
Report #008
Atlantic Wind Test Site, Prince Edward Island, Canada
July 1981

B-19 M.A. Lodge, R.G. Richards
ATLANTIC WIND TEST SITE
Report #009
Atlantic Wind Test Site, Prince Edward Island, Canada
April 1981

B-20 M.A. Lodge, R.G. Richards
2KW DUNLITE FAILURE REPORT
Report #010
Atlantic Wind Test Site, Prince Edward Island, Canada
November 1983

B-21 R.G. Richards
PELLWORM, RISO AND ECN WIND TURBINE TEST FACILITIES, VISIT REPORT
Report #011
Atlantic Wind Test Site, Prince Edward Island, Canada
May 1983

B-22 M.A. Lodge
PREPARATION OF A TEST BED FOR A FUTURE ANEMOMETER COMPARISON PROJECT AT THE ATLANTIC WIND TEST SITE

Report #012
Atlantic Wind Test Site, Prince Edward Island, Canada
March 1983

B-23 M.A. Lodge
PROJECT AQUILO SITE PREPARATION AND SERVICES AT THE ATLANTIC WIND TEST SITE
Report #013
Atlantic Wind Test Site, Prince Edward Island, Canada
December 1983

B-24 R.G. Richards
VAWT DRIVE TRAIN DYNAMICS - A DESIGN CASE HISTORY
Report #014
Atlantic Wind Test Site, Prince Edward Island, Canada
1981

B-25 M.A. Lodge
WIND ENERGY CONVERSION SYSTEMS & THEIR APPLICATION TO BUILDINGS 1981/2001
Presented at "Building Towards 2001 - New Energy Forms in the Building Environment"
Report #015
Atlantic Wind Test Site, Prince Edward Island, Canada
November 1981

B-26 THE ENERGY CONTAINED IN THE WIND AND HOW IT IS EXTRACTED
Report #016
Atlantic Wind Test Site, Prince Edward Island, Canada
August 1982

B-27 G. Petersen, R. Richards
INVESTIGATION INTO THE EFFECTS OF DATA AVERAGING INTERVAL AND ANEMOMETER - ROTOR SPACING ON THE EVALUATION OF WECS PERFORMANCE DATA
Report #017
Atlantic Wind Test Site, Prince Edward Island, Canada
May 1983

B-28 SYSTEM EFFICIENCY OF A EURODRIVE GEARBOX/GENERATOR USED AS THE DRIVE TRAIN OF A 9 × 6 m VAWT
Report #018
Atlantic Wind Test Site, Prince Edward Island, Canada

B-29 PROJECT AQUILO SIGNAL CONDITIONING AND COMMISSIONING OF INSTRUMENTATION AND MONITORING SYSTEM
Report #019
Atlantic Wind Test Site, Prince Edward Island, Canada
May 1984

B-30 DESIGN AND DEVELOPMENT OF A ROTOR STRESS MONITORING TELEMETRY SYSTEM FOR WIND ENERGY CONVERSION SYSTEMS
Report #020
Atlantic Wind Test Site, Prince Edward Island, Canada
October 1984

B-31 AN INVESTIGATION AND ASSESSMENT OF PROCEDURES TO MEASURE AND PROCESS WIND ENERGY CONVERSION SYSTEM PERFORMANCE DATA AT THE ATLANTIC WIND TEST SITE
Report #021
Atlantic Wind Test Site, Prince Edward Island, Canada
June 1984

B-32 PRELIMINARY DATA ACQUISITION FOR PROJECT AQUILO
Report #022
Atlantic Wind Test Site, Prince Edward Island, Canada
March 1985

B-33 M. Lodge, C. Brothers
ANEMOMETER COMPARISON PROJECT
Resource Venture Inc., Charlottetown, Prince Edward Island

B-34 C. Brothers
FIELD TEST OF CANADIAN STANDARDS ASSOCIATION WIND ENERGY CONVERSION SYSTEMS, PERFORMANCE STANDARD F417
Atlantic Wind Test Site, Prince Edward Island, Canada
March 31, 1986

14.3 Atmospheric Environment Service Reports

The AES contact for information and services is:

Energy and Industrial Applications Section (CCAI/I)
Canadian Climate Center
Environment Canada
4905 Dufferin Street
Downsview, Ontario
M3H 5T4 Telephone (416) 667-4626

C-1 Alberta Research Council
THE ANALYSIS OF WIND DATA FOR WIND POWER RESOURCES ASSESSMENT
Contractor's report prepared for the Atmospheric Environment Service
Downsview, Ontario
December 1983

C-2 Atmospheric Environment Services
CANADIAN CLIMATE NORMALS, 1951-1980, VOLUME 5, WIND
Downsview, Ontario
1982

C-3 W.C. Bell
COLLECTION AND ANALYSIS OF WIND DATA AND TEMPERATURE DATA TO DETERMINE WIND DISTRIBUTION IN THE LOWEST 250 METRES
Contractor's report prepared for the Atmospheric Environment Service
Downsview, Ontario
March 1982

C-4 R.L. Berry, P.A. Taylor
WIND ENERGY IN THE LOWER ST. LAWRENCE RIVER VALLEY AND SITE EVALUATION FOR PROJECT AEOLUS
Proc. 4th International Symposium on Wind Energy Systems held at Stockholm
Sweden
September 1982

C-5 Concord Scientific Corporation
AEOLUS PROJECT WIND RESOURCE ASSESSMENT: PRELIMINARY ANALYSIS OF WIND DATA FOUNDERIE SITE; September-November 1981
Contractor's report prepared for the Atmostpheric Environment Service
Downsview, Ontario
June 1982

C-6 Concord Scientific Corporation
WINDAT: COMPUTER PROGRAM FOR STATISTICAL ANALYSIS OF WIND DATA - USER'S GUIDE AND DESCRIPTION
Contractor's report prepared for the Atmospheric Environment Service
Downsview, Ontario
July 1982

C-7 Concord Scientific Corporation
PROFILE: A COMPUTER PROGAM FOR STATISTICAL ANALYSIS OF WIND DATA - USER'S GUIDE AND CODE DESCRIPTION
Contractor's report prepared for the Atmospheric Environment Service
Downsview, Ontario
October 1982

C-8 Concord Scientific Corporation
DEVELOPMENT AND VALIDATION OF A GEOSTROPHIC WIND/VERTICAL PROFILING MODEL, PHASE 1 REPORT
Contractor's report prepared for the Atmospheric Environment Service
Downsview, Ontario
February 1984

C-9 Concord Scientific Corporation
DEVELOPMENT AND VALIDATION OF A GEOSTROPHIC WIND/VERTICAL PROFILING MODEL, PHASE 2 REPORT
Contractor's report prepared for the Atmospheric Environment Service
Downsview, Ontario
October 1984

C-10 Meteorological and Environmental Planning, Ltd
STANDARDIZATION OF ARCHIVED WIND DATA TO A CONSTANT HEIGHT
Contractor's report prepared for the Atmospheric Environment Service
Downsview, Ontario
October 1979

C-11 R.J. Morris
EVALUATION OF METHODS OF FITTING THE WEIBULL DISTRIBUTION TO OBSERVED WIND SPEED DISTRIBUTION FOR WIND ENERGY APPLICATIONS
Proc. 1st Annual Canadian Wind Energy Conference
Ottawa, Canada
December 9-10, 1985

C-12 R.J. Morris, D.G. Howell
WIND ENERGY ANALYSES FOR CANADA
Proc. 10th Annual Conf. of the Solar Energy Society of Canada, Inc.
Calgary, Alberta
August 2-6, 1984

C-13 J.R. Salmon
PROCESSSING AND ANALYSIS OF INITIAL DATA FROM THE ST. LAWRENCE STUDY
Contractor's report prepared for the Atmospheric Environment Service
Downsview, Ontario
November 1983

C-14 P.A. Taylor, R.J. Lee
SIMLE GUIDELINES FOR ESTIMATING WIND SPEED VARIATIONS DUE TO SMALL SCALE TOPOGRAPHIC FEATURES
Climatological Bulletin, Volume 18, Number 2,
October 1984

C-15 P.A Taylor, J.R. Salmon, R.L. Berry
A PRELIMINARY REPORT ON THE WIND ENERGY ASSESSMENT OF THE THREE SITES IN THE LOWER ST. LAWRENCE VALLEY
Report ARQB-81-032-L, Atmospheric Environment Service
Downsview, Ontario
December 1981

C-16 P.A. Taylor, H.W. Teunissen
ASKERVEIN '82: REPORT ON THE SEPTEMBER/OCTOBER 1982 EXPERIMENT TO STUDY BOUNDARY LAYER FLOW OVER ASKERVEIN, SOUTH UIST
Report MSRB-83-8, Atmospheric Environment Service
Downsview, Ontario
November 1983

C-17 P.A. Taylor, H.W. Teunissen
THE ASKERVEIN HILL PROJECT: REPORT ON THE SEPTEMBER/OCTOBER 1983 MAIN FIELD EXPERIMENTS
Report MSRB-84-6, Atmospheric Environment Service
Downsview, Ontario
December 1985

C-18 P.A. Taylor, H.W. Teunissen, R. Johnson
THE ASKERVEIN EXPERIMENTS
Proc. 7th British Wind Energy Conf.,
Oxford, U.K.
March 27-29, 1985

C-19 P.A. Taylor, J.L. Walmsley, J.R. Salmon
A SIMPLE MODEL OF NEUTRALLY STRATIFIED BOUNDARY LAYER FLOW OVER REAL TERRAIN INCORPORATING WAVENUMBER-DEPENDENT SCALING
Boundary Layer Meteorology, 26, 169-189

C-20 H.W. Teunissen, M.E. Shokr
THE ASKERVEIN HILL PROJECT: WIND TUNNEL SIMULATION (SMOOTH MODEL) AT LENGTH SCALE 1:1200
Report MSRB-85-1, Atmospheric Environment Service
Downsview, Ontario
April 1985

C-21 H.W. Teunissen, M.E. Shokr
WIND TUNNEL/FULL SCALE MEASUREMENTS AND MODEL COMPARISONS OF WIND FLOW OVER AN ISOLATED HILL
Proc. Fifth U.S. National Conf. on Wind Engineering, held at Texas Tech University
Lubbock, Texas,
November 6-8, 1985

C-22 S. Venkatesh, R.G. Jessup
APPLICATION OF THE SMALL AREA MODEL FOR THE SITING OF WIND ENERGY CONVERSION SYSTEMS
Attachment to I.E.A. Annex II report: An Evaluation of the Role of Wind Field Models in Wind Turbine Siting
1982

C-23 Atmospheric Environment Services
WIND ENERGY ANALYSES FOR CANADA: 1967-76
Volume 1: Atlantic Provinces
Volume 2: Quebec
Volume 3: Ontario
Volume 4: Prairie Provinces
Volume 5: British Columbia
Volume 6: Yukon and Northwest Territories
May 1986

C-24 J.L. Walmsley, J.R. Salmon
A BOUNDARY LAYER MODEL FOR FLOW OVER HILLS: COMPARISON OF MODEL RESULTS WITH ASKERVEIN 1983 DATA
Proc. European Wind Energy Conference, paper A14
Hamburg
October 1984

C-25 P.A. Taylor
ON WAKE DECAY AND ROW SPACING FOR WECS FARMS
Proc. 3rd Intn'l Symposium on Wind Energy Systems, pp 451-468
Lyngby, Denmark
August 1980

C-26 P.A. Taylor
WAKE DECAY AND POWER REDUCTION IN WIND FARM ARRAYS - AN APPLICATION TO THE ARRAY PROPOSED FOR KAHUKU HILLS
Wind Engineering, 4, pp 76-79
1980

14.4 International Energy Agency References

D-1 Kernforschungsanlage Jülich GmbH
IEA LS WECS: First Meeting Of Experts
SEMINAR ON STRUCTURAL DYNAMICS
Report Jül-Spez-28, ISSN 0343-7639
Munich
October 1978

D-2 Kernforschungsanlage Jülich GmbH
IEA LS WECS: Second Meeting Of Experts
CONTROL OF LS-WECS AND ADAPTION OF WIND ELECTRICITY TO THE NETWORK
Report Jül-Spez-40, ISSN 0343-7639
Munich
April 1979

D-3 Kernforschungsanlage Jülich GmbH
IEA LS WECS: Third Meeting Of Experts
ATA ACQUISITION & ANALYSIS FOR LS WECS
Report Jül-Spez-71, ISSN 0343-7639
Munich
September 1979

D-4 Kernforschungsanlage Jülich GmbH
IEA LS WECS: Fourth Meeting Of Experts
ROTOR BLADE TECHNOLOGY WITH SPECIAL RESPECT TO FATIQUE DESIGN PROBLEMS
Report Jül-Spez-82, ISSN 0343-7639
Munich
April 1980

D-5 Kernforschungsanlage Jülich GmbH
IEA LS WECS: Fifth Meeting of Experts
ENVIRONMENTAL AND SAFETY ASPECTS OF THE PRESENT LARGE SCALE WECS
Report Jül-Spez-100, ISSN 0343-7639
Munich
September 1980

D-6 Kernforschungsanlage Jülich GmbH
IEA LS WECS: Sixth Meeting Of Experts
RELIABILITY AND MAINTENANCE PROBLEMS OF LS WECS
Report Jül-Spez-129, ISSN 0343-7639
Munich
April 1981

D-7 Kernforschungsanlage Jülich GmbH
IEA LS WECS: Seventh Meeting Of Experts
COSTING OF WIND TURBINES Report Jül-Spez-129, ISSN 0343-7639
Munich
March 1982

D-8 Kernforschungsanlage Jülich GmbH
IEA LS WECS: Eighth Meeting Of Experts
SAFETY ASSURANCE AND QUALITY CONTROL OF LS WECS DURING ASSEMBLY, ERECTION, AND ACCEPTANCE TESTING
Report Jül-Spez-203, ISSN 0343-7639
Munich
April 1983

D-9 Kernforschungsanlage Jülich GmbH
IEA LS WECS: Ninth Meeting Of Experts
STRUCTURAL DESIGN CRITERIA FOR LS WECS
Report Jül-Spez-225, ISSN 0343-7639
Munich
October 1983

D-10 Kernforschungsanlage Jülich GmbH
IEA LS WECS: Tenth Meeting Of Experts
UTILITY AND OPERATIONAL EXPERIENCES AND ISSUES FROM MAJOR WIND INSTALLATIONS
Report Jül-Spez-249, ISSN 0343-7639
Munich
October 1983

D-11 Kernforschungsanlage Jülich GmbH
IEA LS WECS: Eleventh Meeting Of Experts
GENERAL ENVIRONMENTAL ASPECTS OF LARGE SCALE WIND ENERGY UTILIZATION
Report Jül-Spez-278, ISSN 0343-7639
Munich
May 1984

D-12 Kernforschungsanlage Jülich GmbH
IEA LS WECS: Twelfth Meeting Of Experts
AERODYNAMIC CALCULATION METHODS FOR WECS
Report Jül-Spez-304, ISSN 0343-7639
Copenhagen
March 1985

D-13 Kernforschungsanlage Jülich GmbH
IEA LS WECS: Thirteenth Meeting Of Experts
PETTEN, ECONOMIC ASPECTS OF WIND TURBINES
(in publication)
May 1985

D-14 Kernforschungsanlage Jülich GmbH
IEA LS WECS: Fourteenth Meeting Of Experts
MODELLING OF ATMOSPHERIC TURBULENCE
(in publication)
December 1985

D-15 International Energy Agency
CO-OPERATION IN THE DEVELOPMENT OF LARGE-SCALE WIND ENERGY SYSTEMS
(IEA LS WECS): ANNUAL REPORT 1985
Published by the IEA LS WECS Executive Committee
January 1986

D-16 International Energy Agency
RPGRAMME OF RESEARCH AND DEVELOPMENT ON WIND ENERGY CONVERSION
SYSTEMS
(IEA R&D WECS): ANNUAL REPORT 1985
Published by the IEA R&D WECS Executive Committee
January 1986

IEA R&D WECS Annex I

D-17 S. Eggwertz et al.
SAFETY OF WIND ENERGY CONVERIOSN SYSTEMS WITH HORIZONTAL AXIS
FFA Technical Note HU-2229
The Aeronautical Institute
Sweden
1981

D-18 E. Kinsella
IEA R&D WECS TASK I, SUB-TASK A2 FINAL REPORT
National Board for Science and Techology
Dublin
1980

D-19 P.J.H. Builtjes
WIND TURBINE WAKE EFFECTS
TNO Report 79-08375
TNO
Apeldoorn
1980

D-20 J.M.G.A. Ouderling, J.T.A. Neesen
AN INVENTORY OF CONDITIONS AND REQUIREMENTS FOR THE INSTALLATION OF LARGE- SCALE WINDMILL NETWORKS WITH RESPECT TO THEIR IMPACT ON TELECOMMUNICATION
PTT Report 475 TM
Dutch PTT, Leidschedam
1981

D-21 S. Engström, B. Pershagen
AESTHETIC FACTORS AND VISUAL EFFECTS OF LARGE-SCALE WECS
NE 1980:20
National Swedish Board for Energy Source Development
Sweden
1980

D-22 S. Bodin, U. Fredriksson
UNCERTAINTY IN WIND FORECASTING FOR WIND POWER NETWORKS
SMHI Report RMK 25
Swedish Meteorologilical and Hyrological Institute
Sweden
1981

D-23 G. Törnkvist
BASIC DESIGN RECOMMENDATIONS FOR WIND ENERGY CONVERTERS
Saab-Scania Report FKL-V-80.9

D-24 G. Törnkvist
DESIGN RECOMMENDATIONS FOR WIND ENERGY CONVERTERS WITH HORIZONTAL AXIS
Saab-Scania Report FKL-V-80.10

D-25 G. Törnkvist
DESIGN RECOMMENDATIONS FOR WIND ENERGY CONVERTERS WITH VERTICAL AXIS
Saab-Scania Report FKL-V-18.11

D-26 B. Pershagen (Ed.)
ENVIRONMENTAL AND METEOROLOGICAL ASPECTS OF WIND ENERGY CONVERSION SYSTEMS FINAL REPORT OF TASK I
NE 1981:25 National Swedish Board for Energy Source Development
1981

IEA R&D WECS Annex II

D-27 W.T. Pennell
AN EVALUATION OF THE ROLE OF NUMERICAL WIND FIELD MODELS IN WIND TURBINE SITING

PNL-SA-11129
Battelle Pacific Northwest Laboratories
1983

IEA R&D WECS Annex III

D-28 L. Jarass, L. Hoffmann, A. Jarass, G. Obermair
WIND ENERGY: AN ASSESSMENT OF THE TECHNICAL AND ECONOMIC POTENTIAL. A CASE STUDY OF THE FEDERAL REPUBLIC OF GERMANY
Springer Verlag
1981

D-29 W. Dub, H. Pape
INTERGRATION OF WIND POWER INTO NATIONAL ELECTRICITY SUPPLY SYSTEMS
FINAL REPORT OF TASK IIIa
University of Regensburg
1982

IEA R&D WES, Annex IV

The following reports were published during 1979-80 by the Institute für Aerodynamik und Gasdynamik and the Institute für Statik and Dynamik der Luft und Raumfahrtkonstruktionen of the University of Stuttgart, Germany, in conjunction with IEA, R&D, WECS, ANNEX IV

D-30 F.X. Wortmann
TRAGFLUGELPROFILE FUR WINDTURBINEN

D-31 J.H. Argyris, K.A. Braun
LASTWECHSELZAHLEN AND MATERIALWERTE FUR DIE AUSLEGUNG EINER WINDTURBINE SPEZIELLEN NABEN-KONSTRUKTION

D-32 J.H. Argyris, K.A. Braun, B. Kirchgässner
STATISCHE UNTERSUCHUNG VON ROTORBLATTERN UNTER EIGENGEWICHT UND IM STATIONAREN BETRIEB

D-33 G.A. Walter
THE INFLUENCE OF AIRFOIL PROPERTIES ON THE FLAPPING MOTION AND ROTOR FORCES OF TWO-BLADED WIND TURBINES WITH FLAPPING HINGES AND FLAP-PITCH COUPLING UNDER GUST LOADING

D-34 S. Mickeler
AN ANALYTICAL INVESTIGATION RELATING TO TWO-BLADED WIND TURBINES WITH FLAPPING HINGES AND FLAP-PITCH COUPLING AT MAINS-DRIVEN OPERATION

D-35 M. Mayer
ONE-BLADED TURBINE WITH TORSIONALLY-COMPLIANT AND PARTIALLY-HINGED BALANCING MASS

D-36 F.X. Wortmann
A GUST GENERATOR FOR WIND TURBINES

D-37 J.H. Argyris, K.A. Braun, B. Kirchgässner
DYNAMIC ANALYSIS OF A ROTOR BLADE WITH FLAP AND LAG FREEDOM AND FLAP-PITCH COUPLING

D-38 J.H. Argyris, B. Kirchgässner
STABILITY AND RESPONSE TO GRAVITY OF THE FLAP-LAG MOTION FOR RIGID ROTOR BLADE WITH FLAP-PITCH COUPLING

D-39 J.H. Argyirs, K.A. Braun
STATIC AND DYNAMIC INVESTIGATIONS OF DIFFERENT TOWERS FOR WIND TURBINES

D-40 J.H. Argyris, K.A. Braun, B. Kirchgässner, R. Walther
STATIC AND DYNAMIC INVESTIGATIONS FOR THE MODEL OF A WIND ROTOR

D-41 J.H. Argyris, W. Aicher, F. Karl, W. Kümmerle, M. Müller
ROTOR MODEL FOR THE VERIFICATION OF COMPUTATIONAL MODELS

IEA R&D WECS, Annex V

D-42 P.J.H. Builtjes, D.J. Milborrow
MODELLING OF WIND TURBINE ARRAYS
Proc. Third Inernational Symposium on Wind Energy System
Copenhagen, Denmark
August 1980

D-43 P.E.J. Vermeulen
AN EXPERIMENTAL ANALYSIS OF WIND TURBINE WAKES
Proc. Third International Symposium on Wind Energy Systems
Copenhagen, Denmark
August 1980

D-44 B.R. Clayton, P. FIlby
WIND TURBINE WAKE STUDIES
Proc. Third BWEA Wind Energy Conference
Cranfield
April 1981

D-45 D.J. Milborrow
MEASUREMENT AND INTERPRETATION OF WIND TURBINE WAKE DATA
Proc. Third BWEA Wind Energy Conference
Cranfield
April 1981

D-46 J.N. Ross, J.F. Ainslee
WAKE MEASUREMENTS IN CLUSTERS OF MODEL WIND TURBINES USING LASER DOPPLER ANEMOMETRY
Proc. Third BWEA Wind Energy Conference
Cranfield,
April 1981

D-47 P.E.J. Vermeulen
PRACTICAL APPLICATIONS OF A MATHEMATICAL WAKE INTERACTION MODEL
Proc. Fourth International Symposium Wind Energy Systems
Stockholm, Sweden
September 1982

D-48 P.H. Alfredsson
A COMPARISON BETWEEN PREDICTED AND MEASURED DATA FROM WIND TURBINE WAKES
Wind Engineering 6 No. 3 149
1982

D-49 D.J. Milborrow, P.E.J. Vermeulen, J.F. Ainslee
A STUDY OF WAKE EFFECTS BEHIND SINGLE TURBINES AND IN WIND TURBINE PARKS FINAL REPORT
TNO Report 84002609
TNO, Apeldoorn
1984

IEA R&D WECS, Annex VI

C-16 P.A. Taylor, H.W. Teunissen
ASKERVEIN '82: REPORT ON THE SEPTEMBER/OCTOBER 1982 EXPERIMENT TO STUDY BOUNDARY LAYER FLOW OVER ASKERVEIN, SOUTH UIST
Report MSRB-83-8, Atmospheric Environment Service
Downsview, Ontario
November 1983

C-19 P.A. Taylor, J.L. Walmsley, J.R. Salmon
A SIMPLE MODEL OF NEUTRALLY STRATIFIED BOUNDARY LAYER FLOW OVER REAL TERRAIN INCORPORATING WAVENUMBER-DEPENDENT SCALING
Boundary Layer Meteorology, 26, 169-189

C-24 J.L. Walmsley, J.R. Salmon
A BOUNDARY LAYER MODEL FOR FLOW OVER HILLS: COMPARISON OF MODEL RESULTS WITH ASKERVEIN 1983 DATA
Proc. European Wind Energy Conference, paper A14.
Hamburg
October 1984

Recommended Practices for Wind Turbine Testing and Evaluation

D-50 B. Maribo Pedersen
ON RECOMMENDED PRACTICES FOR WIND TURBINE TESTING AND EVALUATION
Proc. Forth Int Symp Wind Energy Systems
Stockholm, Sweden
September 1982

D-51 S. Frandsen, A.R. Trenka, B. Maribo Pedersen (Eds)
RECOMMENDED PRACTICES FOR WIND TURBINE TESTING: VOL 1 POWER PERFORMANCE TESTING
1. Edition
1982

D-52 J. Nitteberg (Ed.)
RECOMMENDED PRACTICES FOR WIND TURBINE TESTING: VOL 2 ESTIMATION OF COST OF ENERGY FROM WIND ENERGY CONVERSION SYSTEMS
1. Edition
1983

D-53 J.W.M. Dekker, E. Jensen, H.H. Ottens, S-E Thor, U. Hassan (Eds.)
RECOMMENDED PRACTICES FOR WIND TURBINE TESTING: VOL 3 FATIGUE CHARACTERISTICS
1. Edition
1984

D-54 S. Ljunggren, A. Gustafsson, A.R. Trenka (Eds.)
RECOMMENDED PRACTICES FOR WIND TURBINE TESTING: VOL 4 ACOUSTICS. MEASUREMENT OF NOISE EMISSION FROM WECS
1. Edition
1984

D-55 L.J. Ballard, R.H. Swansborough (Eds.)
RECOMMENDED PRACTICES FOR WIND TURBINE TESTING: VOL 7 QUALITY OF POWER. SINGLE GRID-CONNECTED WECS
1. Edition
1984

D-56 A.L. Gustafsson
IEA RECOMMENDED PRACTICES FOR WIND TURBINE TESTING AND EVALUATION
Paper T1, the European Wind Energy Conference
Hamburg, Germany
October 23-26, 1984

D-57 EVALUATION OF IEA WIND ENERGY RESEARCH 1977-1981
NE 1982:8
National Swedish Board for Energy Source Development
1982

D-58 B. Pershagen, B. Maribo Pedersen, E. Kinsella
THE INTERNATIONAL ENERGY AGENCY WIND ENERGY COOPERATION
Paper U1, the European Wind Energy Conference
Hamburg, Germany
October 23-26, 1984

14.5 Contractor Reports

E-1 TES Limited
VERTICAL AXIS WIND TURBINE TECHNICAL SUMMARY FOR 1981
TES Report No. C348-2
April 1982

E-2 TES Limited
VERTICAL AXIS WIND TURBINE AND WIND PROSPECTING SITE TECHNICAL SUMMARY FOR 1982
TES Report No. C414-9
March 1983

E-3 TES Limited
VERTICAL AXIS WIND TURBINE AND WIND PROSPECTING SITE TECHNICAL SUMMARY FOR 1983
TES Report No. C480-Final
April 1984

E-4 TES Limited
NRC VERTICAL AXIS WIND TURBINE AND WIND PROSPECTING PROGRAM: 1983 SITE TECHNICAL SUMMARY
TES Report No. C480-11 (Rev. 1)
July 1984

E-5 TES Limited
NRC VERTICAL AXIS WIND TURBINE AND WIND PROSPECTING PROGRAM: 1984 SITE TECHNICAL SUMMARY
TES Report No. C561-11
March 1985

E-6 TES Limited
VERTICAL AXIS WIND TURBINE AND WIND PROSPECTING SITE DATA ANALYSIS: FINAL REPORT FOR 1984
TES Report No. C561-Final
April 1985

E-7 TES Limited
NRC VERTICAL AXIS WIND TURBINE AND WIND PROSPECTING PROGRAM: 1985 SITE TECHNICAL SUMMARY
TES Report No. C6239-11
March 1986

E-8 TES Limited
NRC WIND ENERGY PROSPECTING PROGRAM SUMMARY REPORT
TES Report No. C753-Final
June 1986

E-9 Canadian Standards Association
SWECS SAFETY AND DESIGN CRITERIA
Preliminary Standard F416-M1985
1985

E-10 Canadian Standards Association
WECS PERFORMANCE
Preliminary Standard F417-M1986
January 1986

E-11 Canadian Standards Association
WECS INTERCONNECTION TO THE ELECTRIC UTILITY
Preliminary Standard F418-M1986
March 1986

E-12 Canadian Standards Association
SWECS SITING GUIDELINES
Preliminary Guidelines F428-M1986
August 1986

E-13 Shawinigan Engineering Company Limited
DESIGN STUDY: LARGE CAPACITY VERTICAL AXIS WIND TURBINE GENERATORS
SECL Report No. 5800-00-2-78
September 1978

E-14 Shawinigan Engineering Company Limited
DESIGN STUDY: LARGE CAPACITY ERTICAL AXIS WIND TURBINE GENERATORS - FOLLOW-ON WORK
SECL Report No. 5800-00-1-78
August 1978

E-15 Shawinigan Engineering Company Limited
PROJECT DEFININTION WORK - FOR THE ENGINEERING DEVELOPMENT, DESIGN, PROCUREMENT, CONSTRUCTION, TEST AND EVALUATION OF A PROTOTYPE 4000 SQUARE METER ROTOR SWEPT AREA, VERTICAL AXIS WIND TURBINE GENERATOR ELECTRIC POWER PLANT
SECL Report No. 5800-01-1-79
July 1979

E-16 Shawinigan Engineering Company Limited
SUPPLEMENT TO PROJECT DEFINITION WORK (1980) - FOR THE ENGINEERING DEVELOPMENT, DESIGN, PROCUREMENT, CONSTRUCTION, TEST AND EVALUATION OF A PROTOTYPE 4000 SQUARE METER ROTOR SWEPT AREA, VERTICAL AXIS WIND TURBINE GENERATOR ELECTRIC POWER PLANT
SECL Report No. 5800-02-1-80
June 1980

E-17 DAF Indal Limited
TECHNOLOGY DEVELOPMENT STUDY OF VERTICAL AXIS AEROGENERATOR SYSTEMS YIELDING THE LOWEST COST OF ENERGY
Task No. 1 - Design of Four Standard VAWTS
October 1981

E-18 DAF Indal Limited
TECHNOLOGY DEVELOPMENT STUDY OF VERTICAL AXIS AEROGENERATOR SYSTEMS YIELDING THE LOWEST COST OF ENERGY
Task No. 2 - Rotor Height Analysis
February 1982

E-19 DAF Indal Limited
TECHNOLOGY DEVELOPMENT STUDY OF VERTICAL AXIS AEROGENERATOR SYSTEMS YIELDING THE LOWEST COST OF ENERGY
Task No. 3 - Rotor Column Analysis
April 1982

E-20 DAF Indal Limited
TECHNOLOGY DEVELOPMENT STUDY OF VERTICAL AXIS AEROGENERATOR SYSTEMS YIELDING THE LOWEST COST OF ENERGY
Task No. 4 - Structural Analysis and Computer Program Development
May 1982

E-21 DAF Indal Limited
TECHNOLOGY DEVELOPMENT STUDY OF VERTICAL AXIS AEROGENERATOR SYSTEMS YIELDING THE LOWEST COST OF ENERGY
Task No. 5 - Installation Techniques
March 1983

E-22 DAF Indal Limited
TECHNOLOGY DEVELOPMENT STUDY OF VERTICAL AXIS AEROGENERATOR SYSTEMS YIELDING THE LOWEST COST OF ENERGY
Task No. 6 - Compound Rotor Analysis
November 1982

E-23 DAF Indal Limited
TECHNOLOGY DEVELOPMENT STUDY OF VERTICAL AXIS AEROGENERATOR SYSTEMS YIELDING THE LOWEST COST OF ENERGY
Task No. 9 - Selection of Preliminary Optimum
April 1982

E-24 DAF Indal Limited
TECHNOLOGY DEVELOPMENT STUDY OF VERTICAL AXIS AEROGENERATOR SYSTEMS YIELDING THE LOWEST COST OF ENERGY
Task No. 10 - Blade Fabrication Methods
January 1984

E-25 DAF Indal Limited
TECHNOLOGY DEVELOPMENT STUDY OF VERTICAL AXIS AEROGENERATOR SYSTEMS YIELDING THE LOWEST COST OF ENERGY
Task No. 11 - Rotor Solidity and Strut Analysis
November 1982

E-26 DAF Indal Limited
TECHNOLOGY DEVELOPMENT STUDY OF VERTICAL AXIS AEROGENERATOR SYSTEMS YIELDING THE LOWEST COST OF ENERGY
Task No. 12, 13, 14 - Transmission/Generator Configuration
1982

E-27 DAF Indal Limited
TECHNOLOGY DEVELOPMENT STUDY OF VERTICAL AXIS AEROGENERATOR SYSTEMS YIELDING THE LOWEST COST OF ENERGY

Task No. 16 - Hydraulic Upper Bearing Analysis
October 1982

E-28 DAF Indal Limited
TECHNOLOGY DEVELOPMENT STUDY OF VERTICAL AXIS AEROGENERATOR SYSTEMS YIELDING THE LOWEST COST OF ENERGY
Task No. 18, 19 - Analysis & Design of the Optimum Configuration
December 1983

E-29 DAF Indal Limited
TECHNOLOGY DEVELOPMENT STUDY OF VERTICAL AXIS AEROGENERATOR SYSTEMS YIELDING THE LOWEST COST OF ENERGY
Task No. 20 - Reliability Study
May 1984

E-30 DAF Indal Limited
TECHNOLOGY DEVELOPMENT STUDY OF VERTICAL AXIS AEROGENERATOR SYSTEMS YIELDING THE LOWEST COST OF ENERGY
Task No. 21 - Final Report
May 1984

E-31 DAF Indal Limited
FORCED RESPONSE ANALYSIS OF VERTICAL AXIS WIND TURBINES
April 1983

E-32 Shawinigan Engineering Company Limited
STUDY OF LARGE WIND TURBINE GENERATORS FOR ELECTRICAL POWER GENERATION
EXECUTIVE SUMMARY
SELC Report No. 5845-02-2-80
July 1980

E-33 GasTOPS Limited
QUASI STEADY STATE COMPUTER MODEL OF WIND/DIESEL POWER PLANTS
Report No. GTL-TR-19-13.2.7
29 March 1985

E-34 GasTOPS Limited
SOFTWARE SPECIFICATION FOR COMPUTER MODELS OF WIND/DIESEL POWER PLANTS
Report No. GTL-TR-19-13.2.4
29 March 1985

E-35 GasTOPS Limited
SYSTEM DESIGN FOR COMPUTER MODELS OF WIND/DIESEL POWER PLANTS

Report No. GTL-TR-19-13.2.2
31 March 1985

E-36 GasTOPS Limited
VALIDATION OF WIND/DIESEL POWER PLANT COMPUTER MODEL
Report No. GTL-TR-19-13.2.6.1
31 March 1985

E-37 GasTOPS Limited
USER'S MANUAL: WIND/DIESEL HYBRID POWER PLANT COMPUTER MODEL
Report No. GTL-TR-19-13.2.8
31 March 1985

E-38 DAF Indal Limited
DEVELOPMENT, INSTALLATION AND TESTING OF A WIND TURBINE DIESEL HYBRID
1979

E-40 DAF Indal Limited
FURTHER DEVELOPMENT AND TESTING OF THE SUDBURY WIND DIESEL HYBRID POWER PLANT
Final Report
3 March 1985

14.6 General References

F-1 Canada Department of Energy, Mines and Resources
ENERGY STRATEGY FOR CANADA: POLICIES FOR SELF-RELIANCE
Minister of Supply and Services Canada, Ottawa, Ontario
Catalogue No. M27-14/1976-1
1976

F-2 Canada Department of Energy, Mines and Resources
NATIONAL ENERGY PROGRAM
October 1980

F-3 Sandmill Bank Research Group for Agriculture Canada
ASSESSMENT OF WIND AS AN ALTERNATE ENERGY SOURCE FOR CANADIAN FARM OPERATIONS AND HOUSEHOLDS
May 1979

F-4 B.A. Paterson, D.R. Baker, and N.E. Jensen
EVALUATION OF SMALL SCALE WIND TURBINES FOR PUMPING WATER IN ALBERTA
Alberta/Canada Energy Resources Research Fund Report ERRF No. RP.89
1985

F-5 D.R. Baker
EVALUATION OF CSA F417 STANDARD "WECS - PERFORMANCE" AS APPLIED TO WATER PUMPING WIND TURBINES
The Lethbridege Wind Turbine Test Site
Lethbridge, Alberta, Canada
1986

F-6 DANISH WECS STANDARD
The Test Station for Wind Mills, RISO National Lab.
P.O. Box 49, DK-4000. Roskilde, Denmark

F-7 J. Barclay and J. Oliver
THE ECONOMICS OF AND MARKET POTENTIAL FOR WIND ENERGY SYSTEMS IN CANADA
Proc. Canadian Wind Energy Conference 85, Ottawa, Ontario
December 1985

F-8 Kaman Aerospace Corporation
DESIGN STUDY OF WIND TURBINES, 50 kW TO 3000 kW, FOR ELECTRIC UTILITY APPLICATIONS, ANALYSIS AND DESIGN"
Report No. ERDA/NASA - 19404-76/2
Washington, D.C.
1976

F-9 I. Parasehivoin
DOUBLE MULTIPLE STREAMTUBE MODEL FOR DARRIEUS WIND TURBINES
Proc. 2nd DOE/NASA Wind Turbine Dynamics Workshop, Cleveland, Ohio
NASA CP-2185
February 1981

F-10 WIND POWER
RESULTS AND CONCLUSIONS FROM THE SWEDISH WIND ENERGY PROGRAM
National Energy Administration 1985:1
(In Swedish with English summary)

F-11 E.L. Petersen, I. Troen, S. Frandsen, and K. Kedagaard
WIND ATLAS FOR DENMARK
Riso National Laboratory Report No. 428
1981

F-12 WINDPOWER: FIVE YEAR RESEARCH PLAN 1985-1990
U.S. Department of Energy
DOE/CE-T11, UC Category:60
January 1985

F-13 J.H. Strickland
THE DARRIEUS TURBINE: A PERFORMANCE PREDICTION MODEL USING MULTIPLE STREAMTUBES
Sandia National Laboratories
Report No. SAND 75-0431

F-14 J.H. Strickland
A VORTEX MODEL OF THE DARRIEUS TURBINE: AN ANALYTICAL AND EXPERIMENTAL STUDY
Sandian National Laboratories
Report No. SAND 79-7058
February 1980

F-15 R.E. Gormont
A MATHEMATICAL MODEL OF UNSTEADY AERODYNAMICS AND RADIAL FLOW FOR APPLICATION TO HELICOPTER ROTORS
U.S. Army Air Mobility R&D Laboratory
Report on Boeing Vertol Contract No. DAAJ02-71-C-0045
May 1973

F-16 D.W. Lobitz
FORCED VIBRATION ANALYSIS OF ROTATING STRUCTURES WITH APPLICATION TO VERTICAL AXIS WIND TURBINES
Proc. Fifth Biennial Wind Energy Conference and Workshop
Report No. SERI/CO-635-1340
October 1981

F-17 D.C. Quarton, J.G. Warren, R.S. Haines, D. Linberg
TURBULENCE INDUCED RESPONSE OF THE ORKNEY 20 m DIAMETER WTG
Eighth British Wind Energy Association Conference, Cambridge
19-21 March 1986